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KERNFORSCHUNGSZENTRUM KARLSRUHE

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INSTITUT FÜR NEUTRONENPHYSIK UND REAKTORTECHNIK

NEUTRON CROSS SECTIONS FOR FAST REACTOR MATERIALS PART I: EVALUATION x)

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KFK 120 (EANDC-E-35 "U")

x) Work performed within the association in the field of fast reactors between the European Atomic Energy Community and Gesellschaft für Kernforschung mbH., Karlsruhe.

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Content

Introduction

This volume is Part I of the tripartite report entitled

"Neutron Cross Sections for Fast Reactor Materials"

Part I: Evaluation

Part II: Tables

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published in one and the same edition as an external report of the Kernforschungszentrum Karlsruhe and as an EANDC report under the reference numbers KFK 120 (EANDC(E)-35"U"). It presents a fairly comprehensive documentation and a critical review of the available experimental and theoretical information on neutron microscopic cross section data and an extensive description of the procedures which were used to elaborate this information into the cross section sets displayed in tabular and graphical forms in KFK 120/ parts II and III. The present work is restricted to those materials which are of primary interest in the design of sodium, steam or He cooled, metal, oxide or carbide fuelled fast reactors with steel, Inconel or Mo canning, i.e.

H, He, C, O, Na, Cr, Fe, Ni, Mo, U^{235}, U^{238} and Pu^{239}

As these cross section data are primarily intended for use in reactor calculations, the neutron energies considered are restricted to the range 0.01 eV to 10 MeV, these being very nearly the lower and upper energy limits of reactor neutrons. In small fast reactors and critical systems neutrons concentrate on keV and MeV energies. Large dilute power reactor systems contain neutrons down to the eV region. Energies down to thermal were considered to render this evaluation useful also for thermal and epithermal reactor calculations. Main emphasis, however, is given to resonance and fast neutron cross sections.

In the energy range quoted above all occurring neutron nuclear interactions are considered. Only those reactions are neglected for which the cross sections fall beyond a lower limit of generally 0.1 mb or, for which the cross section is not known, but is reasonably expected to be very small compared to those for other reactions. The cross section notation, with few exceptions, follows an abbreviated version of the generally accepted nomenclature scheme proposed by Goldstein [1]. The general scheme uses the symbol σ_{xy} to denote the cross section for the (x,y) reaction. In the abbreviated version, applicable, when almost only one bombarding particle is considered as in our case the neutron (x=n), the incident particle subscript may be omitted, i.e. $\sigma_{xy} = \sigma_y$. Accordingly the neutron cross section notation in all three parts of this work is as follows:

σ_T	= total cross section
σ_n	= elastic scattering cross section
$\sigma_n(\theta)$	= differential elastic scattering cross section
$\sigma_{n'}$	= inelastic scattering cross section
$\sigma_{n'}^{Ej}$	= cross section for inelastic excitation of the residual nucleus level Ej (Ej given in MeV)
$\sigma_{n'}(\theta)$	= differential inelastic scattering cross section
σ_γ	= radiative capture cross section
σ_p	= cross section for the (n,p)-process
σ_{np}; σ_{pn}	= cross section for the (n,np); (n,pn)-processes
σ_α	= cross section for the (n,α)-process
$\sigma_{n\alpha}$; $\sigma_{\alpha n}$	= cross section for the (n,nα); (n,αn)-processes
$\sigma_{n'3\alpha}$	= cross section for the (n,n'3α)-process
σ_d	= cross section for the (n,d)-process
σ_t	= cross section for the (n,t)-process
σ_{He^3}	= cross section for the (n,He^3)-process
σ_{2n}	= cross section for the (n,2n)-process
σ_{3n}	= cross section for the (n,3n)-process
σ_f	= fission cross section
σ_a	= $\sigma_\gamma + \sigma_f$ + (σ for all (n,x) reactions, x = charged particle)
σ_X	= $\sigma_T - \sigma_n$ = non-elastic cross section
σ_{tr}	= $\sigma_T - \overline{\mu_L}\,\sigma_n$ = transport cross section

In addition, the following fundamental or derived neutron nuclear data were considered:

$\overline{\mu_L}$	= average of the cosine of the elastic scattering angle in the laboratory system
α	= σ_γ/σ_f
$\bar{\nu}$	= $\bar{\nu}_p + \bar{\nu}_d$ = mean number of secondary neutrons per fission

$\bar{\nu}_p$ = mean number of prompt secondary neutrons per fission

$\bar{\nu}_d$ = mean number of delayed secondary neutrons per fission

η = $\frac{\bar{\nu}}{1+\alpha}$ = effective mean number of secondary neutrons emitted per neutron absorption (for fissionable materials)(except when noted otherwise)

$\chi(E)$ = energy distribution of prompt secondary fission neutrons

All further symbols used are explained in the appropriate places in the text. Elastic scattering angular distributions are not explicitely considered and tabulated, but only used for the evaluation of $\overline{\mu_L}$, i.e. the first coefficient in the Legendre polynomial development of $\sigma_n(\theta)$ in the laboratory system. Concerning the (n,n')-process so far only the scattering to discrete and not to continuously distributed rest nucleus levels is considered. Both these two-dimensional distribution functions will be considered elsewhere. The evaluation of the $\sigma_{n'}^{Ej}$ for an element is always preceded by the discussion of the energy level schemes of its isotopes and an updating and enlargement of the information given in the Nuclear Data Sheets of K. Way et al. [2] (mostly believed to be complete up to 1961) in the light of more recent experiments.

In the physics and safety of fast reactor systems the energetic self-shielding of capture, fission and scattering resonances and the Doppler reactivity coefficient play a particularly important role. For their prediction a reliable and comprehensive knowledge not only of the resonance cross sections, but also of the resonance parametric properties of the reactor materials involved is needed. As a consequence of this importance and of the very large amount of experimental and theoretical investigations available, the compilation, critical discussion and evaluation of this information into recommended sets of resolved and statistical resonance parameters forms a considerable part of this work.

The present volume is organized in six chapters. The subdivision of the whole material follows the subdivision of the whole energy range into thermal, resonance and fast energy subranges which is suggested by the different types of experiments, theoretical interpretation and practical application. Chapter I is devoted to the cross sections, resonance parameters and related data of light nuclei, H, He, C and O in the whole range from thermal to 10 MeV. In chapters II and IV thermal and resonance cross sections and parametric data in the energy regions of resolved and unresolved resonances are treated. These sections are preceded by chapter II in which approximations in the theory of neutron nuclear interactions in the ranges of resolved and statistically distributed resonances are described which are most commonly used in the interpretation of measured resolved or average resonance cross sections and in the calculation of resonance self-shielding factors and Doppler reactivity coefficients. Chapters V and VI finally are devoted to neutron nuclear data of the medium weight and heavy nuclei for fast energies in the ranges of strong resonance overlapping and of almost continuously varying cross sections. The final section contains some general conclusions and, in addition, detailed lists which summarize the uncertainties of the recommended data, the gaps and discrepancies between different experimental and evaluation work and requests for further experimental and evaluation work.

The original title intended for this volume, "Theory and Compilation", has been changed and condensed into "Evaluation". In the past few years this has become the common name for the type of work which we performed and which is described here. Evaluation of cross sections for a certain reaction with a certain nuclide in a given energy range presupposes the compilation of all available experimental material and, in the (frequent) case of gaps and discrepancies, the recourse to nuclear theory (particularly nuclear reaction theory and optical model) and systematics and consists in a critical judgment and comparison of this information with the aim of elaborating it into a complete unequivocal chain of "best" or "recommended" data. In order to be useful for reactor calculations, in particular for further application in the most common multigroup and Monte Carlo computer programs, the energetic tabulation of these data has to be so dense as to reproduce satisfactorily the actual "monochromatic" cross section behaviour and to allow simple interpolation between adjacent values; in our case this is throughout a linear interpolation on a doubly linear scale.

Following these rules, for each individual reaction of each nuclide we have compiled all available references and data contained therein generally beginning with 1950 and ending with the EANDC Conference on the "Study of Nuclear Structure with Neutrons" at Antwerp in July 1965. In some cases still more recent references were considered and important measurements after the Antwerp Conference up to spring 1966 were taken into account as far as possible. For KFK 120/parts II and III the reference deadline was only June 1962. During the composition of part I the number of important experiments and theoretical interpretations raised almost exponentially. This led us to a complete revision and reevaluation of our previously recommended data by taking into account all references up to the deadline mentioned above and explains the subdivision of almost each section into two parts describing the earlier and the present evaluation work, respectively. The present reevaluation being based on much ampler information led to much more comprehensive cross section tables compared with the previous ones; these will shortly be published as the second edition of KFK 120/part II.

Throughout part I it has been tried to assemble the experimental information in survey tables giving reference, year and characteristics of each experiment important for evaluation, i.e. energy range, accuracy, energy resolution, standard etc. mostly together with extensive comments; where appropriate, also the theoretical information was gathered in tables. Tabular or graphical reproduction of all the thousands of data points, which had to be handled in this work, was impossible and not always felt to be worthwhile; this is particularly true of the resonance cross sections of the medium weight and heavy nuclei. If the data were not already documented elsewhere and easily attainable, the following compromise was made. As far as possible and appropriate the experimental data were graphically reproduced; this is true of all fast cross sections for the medium-weight and heavy nuclei and of selected data for the light nuclei. In addition selected important measurements were tabulated. In the resolved and statistical resonance ranges the emphasis was placed on a fairly complete reproduction of the results of the various resonance parameter analyses by the experimenters themselves, in the thermal range on the tabulation, if necessary, of the measured quantities at thermal energy (0.0253 eV). In addition, the references have been arranged according to nuclide, reaction type and energy range in order to facilitate the reference search and the comparison of the present reference lists with existing reference index systems like CINDA (see below). Finally, as far as possible, our previously and presently recommended cross section values are graphically plotted and/or tabulated (in a few cases) together with the experimental data in order to enable a direct comparison.

The evaluation methods used range from selection of individual data sets, simple "eye-guide" curves or least squares fits through the experimental data to semi-empirical or theoretical curves. As a consequence of the rather many gaps and still unexplained discrepancies between different experiments, the non-unique parametric or model character of the nuclear theory and the necessity to finish this work in a finite time, recourse to subjective judgment and physical feelings was almost unavoidable. Among the possible comparisons with integral measurements so far only so-called "clean" integral data like infinite dilute resonance integrals and averages over the fission neutron spectrum were used in order to check the correctness of the differential data. It is hoped that the manner of documentation explained above and the extensive description and checking of the arguments and ways in which we arrived at our conclusions will sufficiently enable the reader to get a complete picture and understanding of our evaluation and to judge on his own, perhaps with conclusions different from ours. At the end of each individual section estimates of the uncertainties of the recommended data are given; throughout these are not rigorous mathematical but rather rough physical estimates on the basis of the inaccuracies of the preferred experimental data and the systematic deviations between different measurements.

Rather many evaluations of microscopic and multigroup cross section sets are available for the nuclides treated here, showing large differences in value, completeness, up-to-dateness and documentation. A comparison with all these evaluations was neither possible nor worthwhile, as the amount of presently available information by far exceeds that available for an evaluation, say, prior to 1963. Therefore, we restricted ourselves to (rather extensive) comparisons with selected recent work. The calculation of group cross sections from our microscopic data with various neutron energy spectrum weightings and comparison with other group cross section sets is done elsewhere. However, the tables HCQ, MEDEL and UPu at the end of chapters I, V and VI contain a fairly comprehensive account of available not only microscopic, but also multigroup cross section sets, of their content and application. For a comprehensive survey, particularly of existing microscopic cross section evaluations over the whole atomic weight range, together with an estimate of their value and completeness with regard to reactor calculations we refer to a recent report of Parker [3].

In order to avoid continuous repetition, very valuable and frequently used standard works on neutron cross sections are omitted from the reference lists. Among these we mention the well-known neutron cross section compilations BNL-325 and BNL-400 of the Brookhaven Sigma Center [4 - 9]. These contain a graphical representation of experimental total and partial neutron cross sections and elastic and inelastic scattering angular distributions for most nuclei in the range 0 to 20 and more MeV together with "best eye-guide" estimates in the form of smooth curves drawn through these data. The resonance cross sections presented are not corrected for neutron energy resolution and Doppler broadening. In addition, the BNL-325 contain "best" values of thermal neutron cross sections and resonance parameters in tabular form. In the text these reports are briefly referred to as BNL-325/1958 etc. In the earlier editions of BNL-325 only the data points were published, in the more recent editions and supplements some characteristic experimental details are given in addition to each reference and data set. Howerton from Livermore in 1958 published a tripartite work which contains extensive tabulations of experimental neutron cross section data for most nuclei together with energy resolutions and experimental uncertainties [10] in the range from 1 keV to 15 MeV. At the same time he performed an evaluation of semi-empirical total and partial neutron cross sections for most nuclides for neutron energies between 0.5 and 15 MeV [11]; the large gaps in experimental information at that time were closed by estimates based upon optical model calculations, nuclear systematics and physical imagination. A few years perimental angular distributions of elastically and inelastically scattered neutrons for most nuclei in the energy range 0 to 15 MeV with the inclusion of uncertainties in energy, scattering angle and differential cross sections [12]. The usefulness of the Brookhaven reports for the present work consisted in allowing a rapid although not complete insight into general cross section trends with energy, gaps in experimental information and a visual comparison of different experimental results, whereas the Livermore reports were of immediate use in gathering the earlier experimental data.

Further references concern the compilation of experimental data for most nuclei specified to certain types of nuclear reactions. Here we mention the recent tables of Chazan from the group of Howerton on experimental neutron-induced total and differential discrete and continuum γ-ray excitation cross sections for neutron energies between 0.1 and 15 MeV [13]. Liskien and Paulsen performed a graphical compilation of experimental (n,p), (n,α) and (n,2n) data for selected nuclei for energies between the respective thresholds and about 20 MeV including particularly useful extensive comments on the individual experiments [14]; this compilation is continuously updated and supplemented. A similar graphical compilation of experimental excitation functions for (n,p); (n,t); (n,α); (n,2n); (n,np) and (n,nα) reactions, however, without comments was made by Jessen et al. [15] for the range of thresholds to 20 MeV. Furthermore Neuert and Pollehn published tables of cross sections for all nuclear reactions with neutrons in the range 14 to 15 MeV together with experimental details [16]. From our definition of evaluation it is clear that all of the above works with few exceptions are compilations of experimental data and as such only prerequisites to evaluation. Frequent use was also made of the recent tables of threshold energies edited by Howerton et al. [17] which correspond to reaction Q-values calculated from the mass tables of König et al. [18]. Finally the Swedish reference surveys of Leimdörfer et al. on neutron inelastic scattering [19] and of Wallin et al. on optical model calculations [20] were found particularly useful.

Of steadily increasing value for the evaluation groups is the activity particularly of the compilation centers at Saclay and Brookhaven which collect experimental neutron nuclear data simultaneously with the respective literature references and distribute this information upon request. An Oak Ridge group, the Saclay group, the IAEA Nuclear Data Unit and a small group at Obninsk/Russia especially take care of the distribution and completion of CINDA (= card index of nuclear data), a mechanized computer reference system for neutron nuclear data originally developed by Goldstein. "CINDA 65" [21] was the first edition of a series of regular publications of the content of this computer reference library which becomes more and more comprehensive and tends to replace effectively the large personal reference lists collected by various evaluators in the past.

All the neutron cross sections and related nuclear data, resolved and statistical resonance parameters presently recommended are stored in the nuclear data file of the Karlsruhe IBM 7074 computer (KEDAK). Shortly the content of the file will be transferred to the neutron data compilation center at Saclay and will then be available upon request.

We hope that this book will help evaluations and reactor physicists to get a fairly comprehensive and consistent idea of our present-day knowledge in the neutron nuclear data field illustrated by the investigation of a restricted number of practically important nuclides and to clarify some of the problems connected with the numerous discussions in the past on different microscopic and multigroup cross section sets. At the same time we hope that it presents useful information for the experimental and theoretical nuclear physicist showing solved together with unsolved problems, gaps and inconsistencies in order to stimulate further work in the field of neutron nuclear interactions.

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all necessary physical and technical details, enabled him to incorporate these data in the early stages of the Karlsruhe Nuclear Data File and in KFK 120/parts II and III.

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Unavoidably a project work of this size suffers from various deficiencies and heterogeneities. The author will be greatly indebted to all those who make him aware of any errors, omissions, misjudgements and shortcomings. In addition he would be very grateful for any comments and suggestions which are likely to help in achieving the aims of this work and to improve the understanding and quantitative knowledge of low energy neutron nuclear interactions.

Finally, I am deeply indebted to my wife for her permanent patience, vivid encouragement and active help in all stages of this project. To her therefore I affectionately dedicate my work.

J. J. Schmidt

Literature references

1. H. Goldstein, "Nomenclature Scheme for Experimental Mono-energetic Nuclear Cross Sections", Appendix I, p. 2227 of "Fast Neutron Physics, Part II, Experiments and Theory", ed. by J.B. Marion and J.L. Fowler, Interscience Publishers, New York - London, 1963
2. K. Way, Nuclear Data Sheets, Nat. Acad. Sci., Nat. Research Council, Washington D.C.; see also K. Way, N.B. Gove, C.L. McGinnis, R. Nakasima, Landolt-Börnstein, New Series, Vol. I, "Energy levels of nuclei: A=5 to A=257", 1961
3. K. Parker, AWRE O-13/65, 1965
4. D.J. Hughes, R.B. Schwartz, BNL-325, 2nd ed., 1958
5. D.J. Hughes, B.A. Magurno, N.K. Brussel, BNL-325, 2nd ed., supplement No 1, 1960
6. J.R. Stehn, M.D. Goldberg, B.A. Magurno, R. Wiener-Chasman, BNL-325, 2nd ed., supplement No. 2, Vol. I, Z=1 to 20, 1964
7. J.R. Stehn, M.D. Goldberg, R. Wiener-Chasman, S.F. Mughabghab, B.A. Magurno, V.M. May, BNL-325, 2nd ed., supplement No. 2, Vol. III, Z=88 to 98, 1965
8. D.J. Hughes, R.B. Schwartz, BNL-400, 1st ed., 1956
9. M.D. Goldberg, V.M. May, J.R. Stehn, BNL-400, 2nd ed., Vol.s I and II, 1962
10. R.J. Howerton, UCRL-5226, Part I, Vol.s I-III, 1958; UCRL-5226-Revised, 1959
11. R.J. Howerton, UCRL-5351, Part II, 1958
12. R.J. Howerton, UCRL-5573, Part III, 1961
13. N. Chazan, UCRL-14007, Rev. 1, August 1965
14. M. Liskien, A. Paulsen, EUR-119.e, 1964
15. P. Jessen, M. Bormann, F. Dreyer, H. Neuert, J. Nuclear Data 1, 103, 1966
16. H. Neuert, H. Pollehn, EUR-122.e, 1963

17. R.J. Howerton, D. Braff, W.J. Cahill, N. Chazan, UCRL-14000, 1964

18. L.A. König, J.H.E. Mattauch, A.H. Wapstra, Nucl. Phys. 31, 18, 1962

19. M. Leimdörfer, E. Bock, L. Arkeryd, AE-88, 1962

20. L. Wallin, A. Persson, M. Leimdörfer, B. Johansson, R. Akselsson, FOA-4-Rapport A-4374-411, April 1964

21. D.W. Colvin, H. Goldstein, "CINDA 65", EANDC-60"U", (NYO-72-107; CCDN-CI/11), May 1, 1965; suppl. No. 1, EANDC-49"U" (NYO-GEN-72-52; CCDN-CI/2), October 15, 1965; suppl. No. 2, EANDC-54"U" (NYO-72-73; CCDN-CI/7), March 1, 1966