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ANGULAR DISTRIBUTIONS IN NEUTRON-INDUCED REACTIONS

VOLUME I, Z = 1 to 22

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INTRODUCTION

This book is a compilation of the most significant experimental observations available in October 1962 on the angular distributions of scattered neutrons and of other products of the reactions of fast neutrons with nuclei. As in the First (1956) Edition, data on elastically scattered neutrons predominate; but there are many distributions for inelastically scattered neutrons; and there are some distributions for charged particles and for gamma rays associated with inelastic neutron scattering. Angular distributions of fission fragments or fission neutrons are not included nor are distributions for which the neutron source is a fission spectrum. Also excluded are distributions for the scattering of slow neutrons, since molecular binding effects may be more important here than nuclear effects.

The compilation is designed to be of use to theorists and experimentalists interested in neutron-interactions and to those concerned with the behavior of neutrons in nuclear reactors and their shields. It gives in considerable detail the results of angular distribution experiments and indicates by whom and how they were obtained and where they are published. It attempts to portray compactly the experimentally known facts and to do so in a manner facilitating interpolation into regions hitherto not covered by experiment.

The book notes in the text, but does not display, angular distributions which the authors reported as purely relative; only absolute differential cross section values are included. Absolute values which were measured at a single angle for a given energy are plotted where other data at that energy have been measured; where no other data are available at that energy, the cross section values are presented in the text and not plotted. There are no theoretically predicted angular distributions shown, and theory played essentially no part in the choice of curves drawn.

With the restrictions just stated, every significant angular distribution measurement known to us is included, except those on hydrogen below 13.7 MeV. Despite older conflicting evidence, it is now generally agreed that scattering by hydrogen is isotropic at those energies. The reader is referred for further details to two review articles, one by J.L. Fowler and J.E. Brolley in *Rev. Mod. Phys.* 28, 103 (1956), the other by W.N. Hess in *Rev. Mod. Phys.* 30, 368 (1958).

The presentation of information in the book is both graphical and textual. The primary angular distribution data are plotted on linear grids for ease in reading off the differential cross section values. A curve is drawn through the data on each graph. This curve is merely our own idea of a reasonable fit to the data; it is an "eye-guide"; it is not a least-squares fit. It is not based on theoretical considerations, but in drawing it we gave considerable weight to any "eye-guide" drawn by the experimentalists when publishing the data. The curve may serve as an arbitrary but widely available standard for those who prefer a curve to the original data but who do not wish to choose a curve themselves. The user of this book should remember that the curve is ours, but that the data are the original authors'; and he should make references accordingly.

On a few secondary comparison survey pages, we have selected curves from the primary plots for subsequent repetition in various forms to illustrate the variation of the angular distributions with neutron energy.

The auxiliary and bibliographic information associated with each graph appears on the page of text opposite the graph. Each pair of pages in the main part of each volume is complete in itself.

ARRANGEMENT

The arrangement of the book is as follows: Volume I covers Elements 1 through 22 (H through Ti). Volume II covers Elements 23 through 94 (V through Pu). In each volume, the first and major part portrays the direct angular distributions, $\sigma(\theta)$ versus cos θ; and an Appendix at the end displays "excitation functions," $\sigma(\theta)$ versus E. Information on the various elements is placed in order of their atomic number, Z. Within any one element, the naturally occurring element comes first, and the various isotopes follow in order of increasing mass number A. For a given Z and A, elastic angular distributions come first, inelastic ones come next (neutrons first, then gamma rays), and those of the charged particles emitted come last. For each type of distribution, the arrangement is in order of increasing neutron energy. The numbering of pages in the book reflects the arrangement just described; a three-number set is used, in which the first number is Z, the second is A (with the definition that A = 0 for the natural element), and the third is merely the sequence number for a given Z and A. Thus, page 4-0-3 is the third pair of pages on natural Be; and page 26-56-1 is the first pair of pages on Fe^{56}.

GRAPHS

The ordinate in all the graphs is the absolute differential cross section, $\sigma(\theta)$, in millibarns per steradian. The label $\sigma(\theta)$ was used as a convenient abbreviation for the more proper notation $d\sigma/d\Omega$. Cross section values are for the natural element, except for the use of isotopic values when a particular isotope is indicated as the target. For the most common type of graph, the abscissa is cos θ, with cos $\theta = +1$ (corresponding to $\theta = 0°$, the forward direction) at the left. Ordinarily the center-of-mass system of coordinates is used for θ and for $\sigma(\theta)$. It is sometimes impossible to transform data published in the laboratory system to the center-of-mass system, so occasionally data are presented in the laboratory system. This generally occurs when distributions are shown for broad energy groups of the outgoing particles. An example is the (n,n') + (n,2n) reaction on Be (see page 4-0-10). The notation CM or LAB is indicated on the abscissa label when appropriate, and occassionally both are used when data in both systems appear on the same page; words on the graph warn when the laboratory system is used in that particular graph alone (for examples, see pages 13-0-13 and 13-0-14). Neutron and other particle energies are always given in the laboratory system.

The ordinate scales sometimes change from one graph to the next; such an occurence is indicated by (NOTE CHANGE IN SCALE). The words (NOTE SUPPRESSED ZERO) serve as a warning that the scale does not start at zero. The forward scattering peak often runs up off the top of the graph at the left. It is then continued on a reduced scale further left with a label such as "× 1/5" indicating the reduction in scale. At least one data point is repeated on both scales in such a case.

The element or isotope is designated at the top outer corner of every page. For elastic scattering distributions, no other notation appears in the margin; other types of reactions are appropriately labelled in the margin.

The laboratory energy of the incident neutrons, in MeV, appears within the block occupied by each graph. If different sets of data taken at nominally different energies appear on the same graph, the types of points associated with each energy are indicated directly below the energy label. Also shown below the energy of the incident neutrons may be the energies of the secondary particles, or the reaction energies (Q values) corresponding to the particles observed, or the level excited in the final nucleus. For uniformity, Q values and level energies quoted are obtained from *Energy Levels of Nuclei: A = 5 to A = 257*, Landolt-Börnstein, New Series, Volume I, Springer-Verlag (1961). The words (SEE TEXT) cover all other complications.

The errors assigned by the original authors are indicated by conventional error flags. Frequently no information on experimental errors are available. When an approximate error value was mentioned in the reference, this is usually quoted in the text. When authors placed typical error flags on some of their points, we do the same. Due to the choice of scale, error bars are sometimes smaller than the size of the symbols used. This is occasionally noted in the text; more often it is implicit in the way errors can be seen to vary on other points from the same source on the graph.

A single symbol represents data taken from a single source, not only on one graph but also on all the graphs appearing on one page; generally the same symbol refers to the same source even on adjoining pages.

In order to show compactly the variation with energy of the shape and magnitude of the angular distributions, a selection of the elastic scattering curves for each element are drawn together on a semilogarithmic plot, similar to the presentation used in the First Edition. These appear at the end of each elastic scattering section. No data points are shown (despite the occasional use of crosses and dots to distinguish one curve from another). The curves are simply free-hand renditions of the more carefully drawn curves on the linear plots discussed above. The user is warned *not* to depend upon the accuracy of values read from these summary curves; the linear curves are the dependable ones. Although many of these survey pages seem cluttered at first sight, it is felt that with a bit of study there is much to be gleaned from such a presentation.

Certain of the light elements have a page or two of a resonance survey presentation, patterned after that used by J.L. Fowler and his co-workers. A set of small-sized replicas of some of the primary linear elastic angular distribution curves discussed previously, but without data points, are displayed beside a representation of the variation of the total cross section with neutron energy. Arrows from each distribution curve indicate the part of the resonance structure investigated. Short lines on the total cross section plot indicate all the energies at which primary angular distribution plots exist, but only a selected few of these are included on the survey presentation. As with the semilogarithmic survey plots discussed just above, these curves are free-hand renditions, and the user should *not* depend upon the accuracy of values read from them. The same is true of the total cross section curves.

One body of data was most compactly presented as plots of $\sigma(\theta)$ vs. E for fixed cos θ, rather than as plots of $\sigma(\theta)$ vs. cos θ for a fixed E (the form used for the primary data discussed above). These came from the measurements of total scattering cross sections by A.S. Langsdorf, R.O. Lane, and their co-workers. Their data are presented in this "excitation function" type of plot in an Appendix at the end of each volume, and separate introductions to these Appendices give complete details regarding the curves.

At many energies, the notation (SEE TEXT) will be found. This generally indicates one of two things: either the measured angular distribution is relative only, or data were taken at only a single angle. For relative data, the text generally gives only the reference, the laboratory and the fact that it is relative, with occassional additional pertinent information. We have not normalized published data, though we have sometimes used, and duly noted, normalizations published in review articles and the like. Very occasionally, absolute data are indicated by the (SEE TEXT) notation, generally where the author has indicated that he feels the data are not in proper form for our use.

A large body of information has been published in which cross sections are determined at only one angle (or at most two angles) for only a few energies. These are more compactly presented in the text rather than in plots of single points. Also given is the same textual information as is given for the absolute angular distribution curves. It should be pointed out that a rather arbitrary distinction is here made between one-angle data measured for a few neutron energies and excitation-function data measured at many energies. We intend to present the excitation-function data in future editions of BNL-325.

TEXT

For convenience in reading and in referencing, information regarding the data plotted is given in close proximity to the data themselves. For this purpose, a text is provided opposite each graph, except for the survey curves mentioned previously. The same symbol as was used in the graph identifies the textual matter for that measurement. The following information, when known, appears in the text for each measurement: reference, laboratory, energy spread, type of experiment, detector used, angular resolution, corrections, normalization, errors, integrated cross section, fitting coefficients, and, occasionally, other pertinent remarks. Conventions adopted for each of these items are described below. It must be emphasized that the text is cryptic and incomplete and is *not* a proper substitute for directly consulting the published reference itself, or for contacting the authors where the facts are important in the use of the data. Although a uniform presentation of the above sequence of items was attempted, exceptions occur when other formats seem best.

Conventions adopted in the text for each of the items of information given are as follows:

References

Usually a single reference is given, in the customary form. In general, both the data themselves and a description of the experimental techniques can be found in the published paper or report so referred to. When a fuller description of the experiment is available elsewhere, reference to this is also made. For experiments and data reported only in abstracts to meetings, private communications with the authors are usually mentioned in addition to the published abstract. Secondary references are also used when they contain pertinent information.

Laboratories

The laboratory at which the experiment was performed, when known, is given in brackets immediately following the reference. Since full names and addresses are usually available in the reference cited, only short well-known forms are used; e.g., "Brookhaven" for the Brookhaven National Laboratory, "Berkeley" for the University of California Radiation Laboratory at Berkeley, "Illinois" for the University of Illinois, and "NRL" for the Naval Research Laboratory.

Energy Spread

The energy spread of the incident neutrons is indicated by ΔE. It is not always clear whether authors are giving a half-width or a full-width spread, but whatever value they give is used. When an author states an energy of 1.0 ± 0.1 MeV, the value of $\Delta E = \pm 0.1$ Mev is noted. If only a target thickness is provided (say of 0.1 MeV) and it is clear that this represents the predominant energy spread, the value $\Delta E \simeq 0.1$ MeV is used. For incident energies greater than 25 MeV, broad energy spectra sources are usually used. For these, when known, an effective ΔE is given, referring to the uncertainty in the mean energy, as well as the ΔE associated with the broad spectrum.

Type of Experiment

The most common geometry used in angular distribution measurements is the standard scattering geometry in which a small scattering sample is placed some distance from a neutron source and a detector is pivoted about the sample to determine the number of neutrons scattered at different angles. For such a geometry no notation is made. When the scatterer is a ring placed about an axis between the source and detector, the notation "Ring geometry" is made. If the target is a gas contained in a counter and the angular distribution is determined by the pulse height distribution of the recoil nuclei, the notaton "Recoil spectrum" or "Recoil proportional counter" is used. No mention of the neutron source is made if an accelerator and standard neutron-producing reaction is used. If neutrons are obtained from photo-neutron sources, from a reactor spectrum, or from some other unusual source, this source is given.

Detectors

Many different neutron detectors have been used to count fast neutrons or charged particles resulting from neutron reactions. Some of the more common are scintillators (solid, liquid, and gas), ionization chambers, proportional counters, Hornyak detectors (molded Lucite-zinc sulphide scintillators), counter telescopes, nuclear emulsions, cloud chambers, and bubble chambers. The various types of solid scintillators are simply designated "Scintillator." When the scintillators, ionization chambers, or proportional counters are biased, this is noted; and the bias energy, when known, is given. Similarly, for counter telescopes, the cutoff energy, when known, is stated. Most ionization chambers and proportional counters are filled with hydrogen or a hydrogenous gas and only other filling gases are noted. Sometimes ranges in nuclear emulsions are mentioned to define the energies of the particles counted. No detectors are recorded for the detection of gamma rays from inelastic scattering; NaI scintillators have almost universally been used. For recoil spectra measurements (see Type of Experiment, above), designations like "Recoil proportional counter" are used.

Angular Resolution

The experimental angular resolution as indicated by $\Delta\theta$. As with the energy spread, it is not always clear whether authors are giving a half-width or full-width resolution, but whatever value they give is used. Angular resolution values are not given in most references since generally they are not important when compared to the shape of the distribution. If the data are corrected for angular resolution, $\Delta\theta$ is not usually given.

Corrections

The most common corrections applied to angular distribution data and noted in the text are for multiple scattering, angular resolution, beam attenuation, end and wall effects, and the presence of inelastically scattered neutrons. Many different methods were used to correct for an effect like multiple scattering, ranging from the simple to the sophisticated; but no attempt was made to evaluate the different methods. If the authors claimed the correction was applied, it is so noted. When nothing is stated about a particular correction, it means that we do not know whether it was made or not. The only exception is the correction for beam attenuation, which is almost always made; and only when it is not do we mention it. Sometimes an author does not make a correction but estimates its size, and this we include. The usual notation, "estimated small," implies that the error in neglecting the correction was less than other contributing errors.

Normalization

When experiments are done absolutely, such as when detectors are placed at the position of the scattering sample in order to determine a scattering ratio, no notation is made. If it was clearly indicated in the reference that normalizations were made with respect to known scattering cross sections or by using integral elastic scattering cross sections obtained in other experiments, this is noted. Actual normalization values are given when known.

Errors

Frequently errors were given on points in published sources without any indication of what error sources they refer to. Some types of errors referred to in the references and used when appropriate in our text are statistical, relative, absolute, normalization, and correction errors. We do not specify whether errors are standard deviations, probable errors, or some other type, for this was rarely indicated by the authors.

Integrated Cross Sections

When authors stated values obtained from some type of integration of their absolute angular distributions, these are given. Unless a shortened angular range is indicated, the integration was over all angles between $\cos\theta = +1$ and -1. We have performed no such integrations.

Fitting Coefficients

Sometimes data are least-squares fitted to some analytic function of angle, usually a sum of Legendre polynomials or a sum of powers of cos θ. When this has been included in the reference, the analytic equation used and the resulting fitting coefficients are tabulated. In a few cases, notably in hydrogen, asymmetry ratios were obtained by the authors, and these are listed. We have computed no least-squares fitting coefficients or asymmetry ratios.

ACKNOWLEDGMENTS

A data compilation such as this could not be prepared without the cooperation and assistance of the many people whose work is being presented. 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. One complementary data source should also be mentioned as being useful: the differential cross section tabulations given by R.J. Howerton in *UCRL-5573* (1961).

We hope for the continued cooperation of experimentalists and other users of this book. Since supplements containing new information will be published from time to time, 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 of this compilation.

Both ours and the reader's tasks have been greatly lightened by the admirable work of the Photography and Graphic Arts Division of the Laboratory. Special thanks are due to G.R. Cox for his assistance in the preparation of the graphs and to R.P. Brown for his work in the publication of the compilation.