

Contents

Part I: Production and Nuclear Interaction of Neutrons

	Page
<i>1. Physical Properties of the Neutron</i>	1
1.1. Historical	1
1.2. Properties of Free Neutrons	2
1.3. Fundamentals of Nuclear Reactions with Neutrons	3
1.3.1. Cross Section, Mean Free Path	3
1.3.2. Classification of Neutron Reactions	5
1.3.3. Properties of the Compound States	8
1.3.4. The Breit-Wigner Formula	9
1.3.5. Cross Sections in the Continuum Region	11
1.4. Experimental Cross Sections	13
1.4.1. Cross Sections of B^{10} , Li^6 , and He^3	13
1.4.2. Cross Sections of Some Moderator Substances	14
1.4.3. The Scattering Cross Section of Crystalline Media at Low Energies	17
1.4.4. The Scattering Cross Section of Free and Bound Nuclei	18
1.4.5. Slow Neutron Cross Sections of the Elements	19
<i>2. Neutron Sources</i>	22
2.1. Neutron Production by Nuclear Reactions	22
2.1.1. The Various Types of Reactions	22
2.1.2. Energetic Considerations	23
2.1.3. Calculation of the Strength of Neutron Sources	25
2.2. Radioactive (α, n) Sources	26
2.2.1. The (Ra—Be) Source	26
2.2.2. Other Neutron Sources of the (α, n) Type	30
2.3. Radioactive (γ, n) Sources	31
2.3.1. Energetic Consideration of the (γ, n) Reaction	31
2.3.2. The (Sb—Be) Source	32
2.3.3. Other Photoneutron Sources	33
2.4. Fission Neutron Sources	34
2.5. Neutron Production with Artificially Accelerated Particles	34
2.5.1. Monoenergetic Neutrons from (p, n) Reactions	35
2.5.2. (d, n) Neutron Sources	38
2.5.3. Utilization of the Bremsstrahlung from Electron Accelerators	40
2.5.4. Production of Quasi-Monoenergetic Neutrons with the Time-of-Flight Method	41
2.6. Principles of Neutron Production in Research Reactors	44
2.6.1. The Various Types of Radiation	44
2.6.2. Experimental Facilities	48
2.6.3. Auxiliary Apparatus for the Production of Monoenergetic Neutrons	49
<i>3. Neutron Detectors</i>	55
3.1. Neutron Detection with the (n, α) Reactions in B^{10} and Li^6	55
3.1.1. The Boron Counter	55
3.1.2. Boron Scintillators	57
3.1.3. Detection Techniques with Lithium-6	58

	Page
3.2. The Detection of Fast Neutrons and the Measurement of Their Energy Using Recoil Protons	59
3.2.1. Simple Recoil Proton Counters	60
3.2.2. Neutron Spectroscopy with Recoil Protons	61
3.3. Other Methods of Detection	62
3.3.1. The Fission Counter	62
3.3.2. The He^3 Detector	63
4. Measurement of Cross Sections	65
4.1. Transmission Experiments	66
4.1.1. Determination of the Total Cross Section	66
4.1.2. Determination of Resonance Parameters	66
4.1.3. The Determination of the Nonelastic Cross Section	69
4.2. Scattering Experiments	70
4.2.1. Elastic Scattering and Angular Distributions	70
4.2.2. Inelastic Scattering	72
4.3. Experiments for Determining Reaction Cross Sections	74
4.4. Experiments on Fissionable Substances	75
4.4.1. Measurement of Fission Cross Sections	76
4.4.2. The Determination of $\bar{\nu}$, η , and α	77
<i>Part II: The Theory of Neutron Fields</i>	
5. Neutron Fields	81
5.1. Characterization of the Field	81
5.1.1. Neutron Flux, Neutron Density, and Neutron Current	81
5.1.2. The General Transport Equation	83
5.1.3. Integral Form of the Transport Equation	85
5.2. Treatment of the Stationary, Energy-Independent Transport Equation. Elementary Diffusion Theory	86
5.2.1. Development in Spherical Harmonics; FICK's Law	87
5.2.2. Asymptotic Solution of the Transport Equation	89
5.2.3. The Neutron Flux in the Vicinity of a Point Source	91
5.2.4. Neutron Flux at the Surface of a Scattering Medium	93
5.2.5. Improved Approximations for the Solution of the Transport Equation	96
5.3. Thermal Neutrons	97
5.3.1. Maxwell Distribution of Energies	98
5.3.2. Reaction Rates in Thermal Neutron Fields	99
5.3.3. The Elementary Diffusion Equation for Thermal Neutrons	101
6. Application of Elementary Diffusion Theory	103
6.1. Extension of the General Theory	103
6.1.1. Elementary Derivation of FICK's Law	103
6.1.2. Diffusion Parameters for Thermal Neutrons	105
6.1.3. The Neutron Flux Near a Point Source: The Significance of the Diffusion Length	105
6.2. Solution of the Diffusion Equation in Simple Cases	106
6.2.1. Simple Symmetrical Sources in Infinite Media	106
6.2.2. General Source Distributions: The Diffusion Kernel	108
6.2.3. Diffusion Problems with Simple Boundary Conditions	110
6.2.4. The Neutron Distribution in a Prism "Pile"	112
6.3. Some Special Diffusion Problems	113
6.3.1. Media in Contact: The Albedo	113
6.3.2. A Strong Absorber in a Neutron Field	115

	Page
7. <i>Slowing Down</i>	116
7.1. Elastic Scattering and Moderation	117
7.1.1. Collision Dynamics	117
7.1.2. Energy and Angular Distribution	119
7.1.3. The Average Logarithmic Energy Decrement	119
7.2. Slowing Down in Hydrogen ($A=1$)	121
7.2.1. Collision Density — Slowing-Down Density — Lethargy	121
7.2.2. Calculation of the Slowing-Down Density and the Energy Spectrum	123
7.3. Slowing Down in Heavy Media ($A \neq 1$)	125
7.3.1. Non-Absorbing Media	125
7.3.2. Absorbing Media: WIGNER's Approximation	127
7.3.3. The Goertzel-Greuling Approximation	130
7.4. Resonance Integrals	131
7.4.1. Definition of the Resonance Integral	131
7.4.2. Calculation of the Resonance Integral with Help of the Breit-Wigner Formula	133
7.4.3. The Doppler Broadening of Resonance Lines	134
7.4.4. Calculation of the Resonance Integral Taking the Doppler Effect into Account	136
8. <i>The Spatial Distribution of Moderated Neutrons</i>	137
8.1. The Mean Squared Slowing-Down Distance	138
8.1.1. Definition of $\bar{r}_E^2$	138
8.1.2. Elementary Calculation of $\bar{r}_E^2$	139
8.1.3. Formulation of an Exact Calculation of $\bar{r}_E^2$	142
8.2. Age Theory	145
8.2.1. The Energy-Dependent Diffusion Equation and Age Theory	145
8.2.2. Age Theory and the Transport Equation	148
8.2.3. Application of the Age Equation to Simple Slowing-Down Problems	150
8.2.4. The Physical Significance of the Fourier Transform of the Slowing-Down Density	153
8.2.5. Inclusion of the First Flight in Age Theory	155
8.3. Other Approximate Methods of Calculating the Slowing-Down Density	157
8.3.1. The Selengut-Goertzel Method	157
8.3.2. The Multigroup Method	158
8.3.3. The B_N -Approximation	161
8.4. The Distribution of Thermal Neutrons Arising from a Specified Fast Neutron Source Distribution	163
8.4.1. The Mean Squared Slowing-Down Distance and the Migration Area	163
8.4.2. Point Source in an Infinite Medium	164
8.4.3. Various Arrangements of Either Point or Plane Sources	165
9. <i>Time Dependence of the Slowing-Down and Diffusion Processes</i>	167
9.1. Slowing Down in Infinite Media	167
9.1.1. Slowing Down in Hydrogen	168
9.1.2. Slowing Down in Heavy Moderators ($A \neq 1$)	170
9.2. The Diffusion of Monoenergetic Neutrons (Pulsed Sources).	173
9.2.1. The Time-Dependent Diffusion Equation.	173
9.2.2. The Validity of the Time-Dependent Diffusion Equation	175
9.3. Age Theory and the Time-Dependent Diffusion Equation	177
9.4. Diffusion of Monoenergetic Neutrons from a Harmonically Modulated Source	179

	Page
<i>10. Thermalization of Neutrons</i>	180
10.1. The Scattering of Slow Neutrons	181
10.1.1. Calculation of $\sigma_s(E' \rightarrow E)$ for an Ideal, Monatomic Gas	182
10.1.2. The General Nature of Neutron Scattering on Chemically Bound Atoms	186
10.1.3. Neutron Scattering in Water, Beryllium, and Graphite	194
10.1.4. Experimental Investigation of Slow Neutron Scattering	198
10.2. The Calculation of Stationary Neutron Spectra	200
10.2.1. The Space-Independent Spectrum in a Heavy Gas Moderator	201
10.2.2. The Space-Independent Spectrum in Real Moderators	207
10.2.3. Basic Facts about Space-Dependent Neutron Spectra	209
10.3. Some Properties of Thermalized Neutron Fields	212
10.3.1. Elementary Treatment of Thermalized Neutron Fields: Diffusion Cooling and Diffusion Heating	213
10.3.2. Treatment of the Diffusion Cooling Effect by the Method of Laguerre Polynomials	217
10.3.3. Transport Theory of the Thermalized Neutron Field	221
10.3.4. Remarks on the Milne Problem for Thermal Neutrons	225
10.4. The Approach to Equilibrium in Pulsed Neutron Fields	226
10.4.1. Elementary Treatment of the Approach to Equilibrium	227
10.4.2. Treatment of Time-Dependent Thermalization as an Eigenvalue Problem	228
<i>Part III: The Determination of Flux and Spectrum in a Neutron Field</i>	
<i>11. Measurement of the Thermal Neutron Flux with Probes</i>	233
11.1. General Facts about Probes	233
11.1.1. Activation and Activity	233
11.1.2. Materials for Thermal Probes	234
11.1.3. The Determination of the Probe Activity	237
11.2. The Theory of the Activity of Neutron-Detecting Foils	239
11.2.1. Activation and the Neutron Flux	240
11.2.2. The Effect of Scattering in the Foil	243
11.2.3. Activation in a Thermal Neutron Field	244
11.2.4. Activation by Neutrons Incident on the Edges of the Foil	245
11.2.5. Calculation of the Apparent Activity Taking Account of β -Self Absorption	246
11.2.6. Activation of a Cylindrical Probe	248
11.3. The Theory of Foil Perturbations	250
11.3.1. Calculation of the Activation Correction with Elementary Diffusion Theory	252
11.3.2. Transport-Theoretic Treatment of the Activation Correction	254
11.3.3. Activation Correction in the Thermal Field	258
11.3.4. Calculation of the Flux Perturbation	259
11.3.5. Activation Perturbation of Tape Probes	260
11.4. Experimental Studies of Foil Perturbations	261
11.4.1. Methods of Measuring the Activation Correction	261
11.4.2. Activation Perturbation in Graphite ($R \ll \lambda_{tr}$)	262
11.4.3. Activation Perturbation in Water and Paraffin ($R \gtrsim \lambda_{tr}$)	262
11.4.4. Measurement of the Flux Perturbation	263
<i>12. Activation by Epithermal Neutrons</i>	265
12.1. Activation by Epithermal Neutrons	265
12.1.1. Approximate Calculation of the Activation	265
12.1.2. Resonance Probes	268
12.1.3. The Sandwich Method	270

	Page
12.2. Simultaneous Thermal and Epithermal Foil Activation	273
12.2.1. The Cadmium Difference Method	273
12.2.2. Calculation of F_{CD} for a Thin $1/v$ -Absorber	274
12.2.3. The Cadmium Ratio and the Determination of the Epithermal Flux	277
12.2.4. The Two-Foil Method	279
12.2.5. Thin Foils: Description According to WESTCOTT's Convention	279
12.3. The Measurement of Resonance Integrals	282
12.3.1. Precise Definition of the Resonance Integral	282
12.3.2. Determination of the Resonance Integral from the Cadmium Ratio	283
12.3.3. Other Methods of Measuring Resonance Integrals	284
13. Threshold Detectors for Fast Neutrons	286
13.1. General Facts about Threshold Detectors	286
13.1.1. Definition of the "Effective Threshold Energy"	286
13.1.2. Substances for Threshold Detectors	289
13.1.3. Fission Chambers as Threshold Detectors	291
13.2. Evaluation of Threshold Detector Measurements	292
13.2.1. "Mathematical" Methods	292
13.2.2. Semi Empirical Methods	293
14. Standardization of Neutron Measurements	296
14.1. Absolute Measurement of Thermal Neutron Fluxes with Probes	296
14.1.1. Probe Substances for Absolute Measurements	297
14.1.2. The Absolute Determination of Probe Activities	298
14.1.3. Electron Self-Absorption in $4\pi\beta$ -Counting	300
14.2. Other Methods of Absolute Flux Measurement	301
14.3. Determination of the Strength of Neutron Sources	303
14.3.1. The Method of Associated Particles	303
14.3.2. The Water-Bath Gold Method	304
14.3.3. Other Total Absorption Methods	306
14.4. Methods for the Comparison of Source Strengths	307
14.5. A Comparison of Various Source-Strength Measurements on (Ra—Be) Sources	310
15. Investigation of the Energy Distribution of Slow Neutrons	312
15.1. Observation of the Differential Spectrum by the Time-of-Flight Method	313
15.1.1. The Problems of Beam Extraction	313
15.1.2. The Chopper Method	315
15.1.3. The Method of Pulsed Sources	319
15.1.4. The Energy Resolution in Time-of-Flight Measurements	321
15.2. Investigation of the Spectrum by Integral Methods	324
15.2.1. Temperature Determination by the Transmission Method	325
15.2.2. Temperature Determination with Lutetium Foils	327
15.2.3. Other Methods of Determining the Neutron Temperature	330
15.3. Results of Measurements of Stationary Spectra	333
15.3.1. Measurements on Water	333
15.3.2. Measurements on Graphite	336
15.3.3. Other Moderators	340
<i>Part IV: The Determination of Neutron Transport Parameters</i>	
16. Slowing-Down Parameters	342
16.1. Determination of the Mean Squared Slowing-Down Distance	342
16.1.1. Basic Facts about the Techniques of Measurement	342
16.1.2. Measurement of the Mean Squared Slowing-Down Distance of Fission Neutrons in Water	344
16.1.3. Results for $\tau_{1.46}^{*2} = 6\tau_{1.46}^{*}$ for Various Media and Sources	346
16.1.4. The Age for Slowing Down from 1.46 eV to Thermal Energy	350

	Page
16.2. The Behavior of the Neutron Flux at Large Distances from a Point Source of Fast Neutrons	351
16.3. The Time Dependence of the Slowing-Down Process	354
16.3.1. Slowing Down to Indium and Cadmium Resonance in Hydrogenous Moderators	354
16.3.2. Slowing Down in Heavy Moderators; The Slowing-Down Time Spectrometer	357
17. <i>Investigation of the Diffusion of Thermal Neutrons by Stationary Methods</i>	360
17.1. Measurement of the Diffusion Length	360
17.1.1. Point Source in an Infinite Medium	360
17.1.2. Finite Media; The Sigma Pile.	362
17.1.3. Determination of the Diffusion Length from the Flux Distribution in a Medium Surrounded by a Surface Source	365
17.1.4. Results of Various Diffusion Length Measurements	368
17.2. Measurement of the Transport Mean Free Path in Poisoning Experiments	372
17.2.1. Principle of the Method	372
17.2.2. Some Experiments on D ₂ O, H ₂ O, and Graphite	373
17.3. Determination of the Absorption Cross Section by Integral Comparison Methods	374
17.3.1. The Method of Integrated Neutron Flux	375
17.3.2. The Mireille Pile Method	376
17.3.3. The Pile Oscillator	378
18. <i>Investigation of the Diffusion, Absorption, and Thermalization of Neutrons by Non-Stationary Methods</i>	383
18.1. Measurements in Thermal Neutron Fields by the Pulsed-Source Method	383
18.1.1. Instrumentation of a Pulsed Neutron Experiment	384
18.1.2. Measurement of the $\alpha(B^2)$ -Curve	385
18.1.3. Results of Pulsed Neutron Studies on Various Moderators	387
18.1.4. Determination of the Geometrical Buckling by the Pulsed Neutron Method	392
18.1.5. Absorption Measurements with the Pulsed Neutron Method	392
18.2. Measurement of the Diffusion Constant by the Method of Modulated Sources	394
18.2.1. Production and Measurement of Modulated Neutron Fields	395
18.2.2. Modulation Experiments on Graphite and D ₂ O	396
18.3. The Study of Neutron Thermalization by the Pulsed Source Method	398
18.3.1. Integral Investigation of the Time-Dependent Spectrum	398
18.3.2. Direct Observations of the Time-Dependent Spectrum	401
<i>Appendix</i>	
I. Table of Thermal Neutron Cross Sections of the Isotopes	407
II. Table of Resonance Integrals for Infinitely Dilute Absorbers (from McARTHUR, PERSIANI <i>et al.</i>)	417
III. Table of the Functions $E_n(x)$	425
IV. Tables of the Functions $\varphi_0(\nu, \beta)$ and $\varphi_1(\nu, \beta)$	430
IV.1. Values of φ_0 as a Function of ν and β	430
IV.2. Values of φ_1 as a Function of ν and β	431
IV.3. Values of φ_1/φ_0 as a Function of ν and β	431
V. Table of Time Factors	432
VI. List of Symbols	435
Subject-Index	440