

# NUCLEAR STRUCTURE PHYSICS

*Editors:*

S. J. HALL  
J. M. IRVINE

Proceedings of the  
Eighteenth Scottish Universities Summer School  
in Physics  
1977

# Nuclear Structure Physics

Proceedings of the Eighteenth Scottish  
Universities Summer School in Physics  
St. Andrews, August 1977

A NATO Advanced Study Institute

*Edited by*

S.J. HALL

University of Glasgow, Scotland.

*and*

J.M. IRVINE

University of Manchester, England.

Published by the  
Scottish Universities Summer School in Physics

SUSSP PUBLICATIONS

Edinburgh University Physics Department  
King's Buildings, Mayfield Road  
Edinburgh.

Further copies of this book may be obtained  
directly from the above address.

Copyright © 1978  
by the Scottish Universities Summer School in Physics

*All rights reserved*

No part of this book may be reproduced in any  
form by photostat, microfilm, or any other means  
without written permission from the publishers.

ISBN 0 905945 01 8

PREVIOUS SUSSP PROCEEDINGS

*Published by Oliver & Boyd (Edinburgh)*

- 1 1960 Dispersion Relations
- 2 1961 Fluctuation, Relaxation and Resonance in Magnetic Systems
- 3 1962 Polarons and Excitons
- 4 1963 Strong Interactions and High Energy Physics
- 5 1964 Nuclear Structure and Electromagnetic Interactions
- 6 1965 Phonons in Perfect and Imperfect Lattices
- 7 1966 Particle Interactions at High Energies
- 8 1967 Mathematical Methods in Solid State and Superfluid Theory
- 9 1968 Physics of Hot Plasmas

*Published by Academic Press*

- 10 1969 Quantum Optics
- 11 1970 Hadronic Interactions of Electrons and Photons
- 12 1971 Atoms and Molecules in Astrophysics
- 13 1972 Electronic/Structural Properties of Amorphous Semiconductors
- 14 1973 Phenomenology of Particles at High Energies
- 15 1974 The Helium Liquids
- 16 1975 Non-Linear Optics

*Published by SUSSP*

- 17 1976 Fundamentals of Quark Models
- 18 1977 Nuclear Structure Physics

*Forthcoming Publications*

- 19 1978 Metal Non-metal Transitions in Disordered Systems

#### EXECUTIVE COMMITTEE

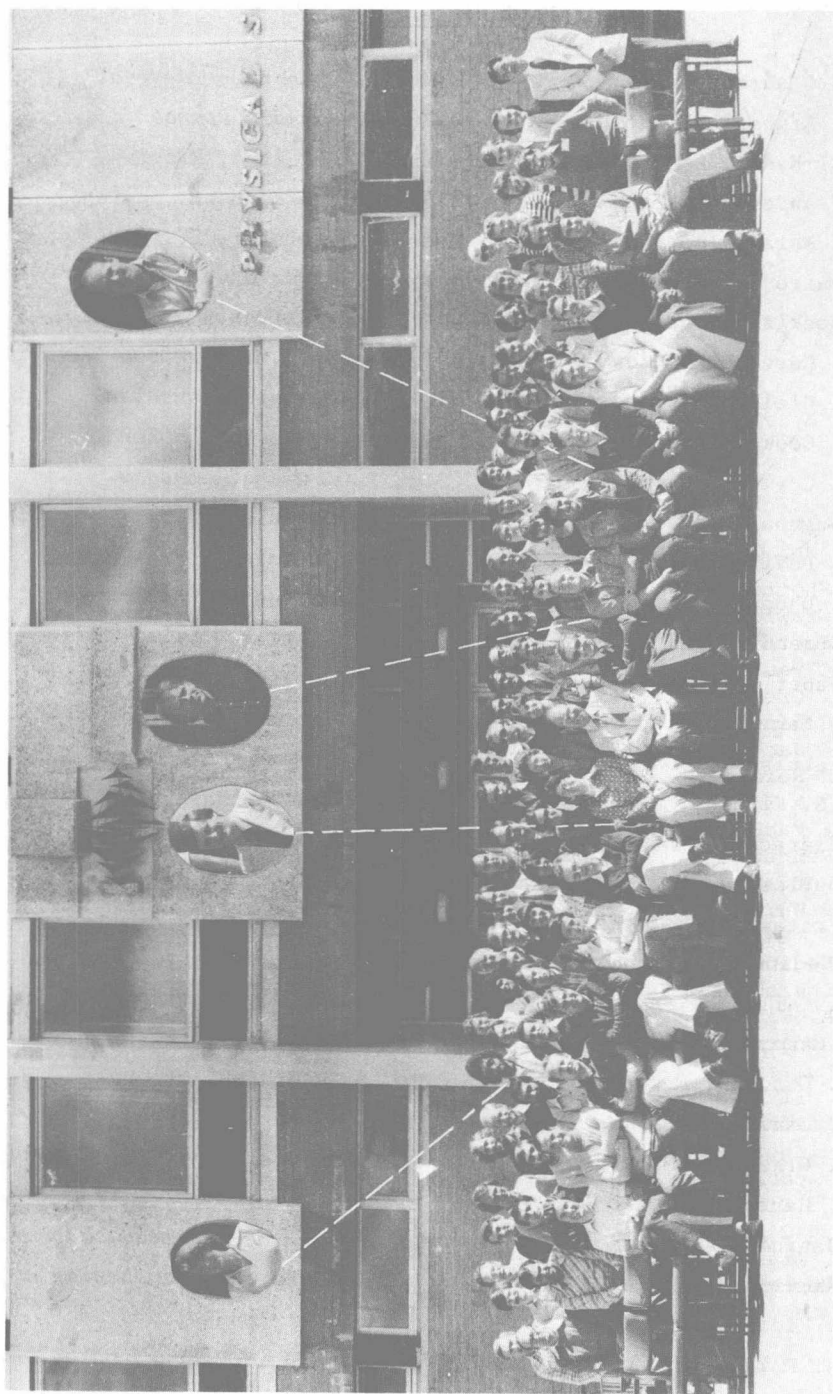
Reid, Professor J.M.,	<i>Glasgow, (Director)</i>
Crawford, Dr. I.	<i>Glasgow, (Secretary)</i>
Whitehead, Dr. R.R.	<i>Glasgow, (Treasurer)</i>
Hall, Dr. S.J.	<i>Glasgow, (Joint Editor)</i>
Irvine, Dr. J.M.	<i>Manchester, (Joint Editor)</i>
Ledingham, Dr. K.	<i>Glasgow, (Social Secretary)</i>
Owen, Dr. R.	<i>Glasgow, (Steward)</i>
Shotter, Dr. A.	<i>Edinburgh, (Steward)</i>
Watt, Dr. A.	<i>Glasgow, (Steward)</i>

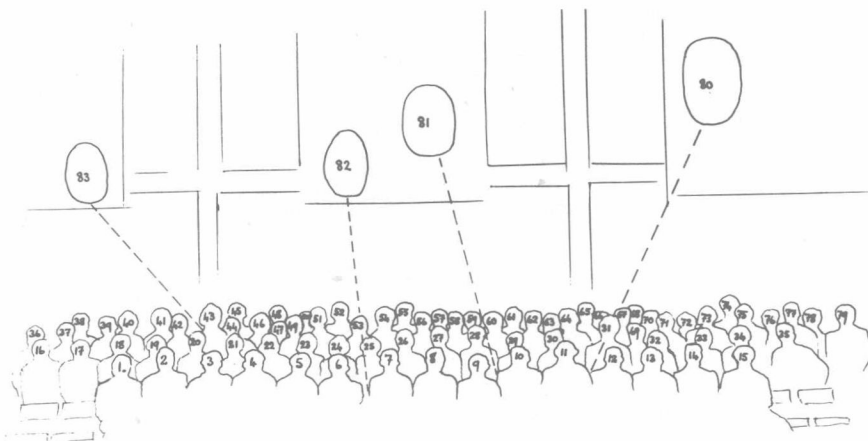
#### LECTURERS

England, Dr. J.B.A.	<i>Birmingham University, U.K.</i>
Green, Professor A.M.	<i>Institute of Theoretical Physics, Helsinki, Finland.</i>
Greiner, Professor W.	<i>Frankfurt University, Germany.</i>
Jackson, Professor D.F.	<i>Surrey University, U.K.</i>
MacFarlane, Professor M.	<i>Argonne National Laboratory, U.S.A.</i>
Pauli, Professor H.C.	<i>Max-Planck Institute, Heidelberg, Germany.</i>
Penner, Dr. S.	<i>N.B.S., Washington D.C., U.S.A.</i>
Scott, Professor D.K.	<i>L.B.L. California University, U.S.A.</i>
Specht, Professor H.J.	<i>Heidelberg University, Germany.</i>
Speth, Professor J.	<i>Institut fur Kernphysik, Julich, Germany.</i>

## PARTICIPANTS

Dr. M da C Abreu, <i>Lisbon</i>	Mr. J.P. Labrie, <i>Montreal</i>
Mr. M.S. Afghani, <i>Bradford</i>	Mr. J. Larysz, <i>France</i>
Mr. A. Al-Naser, <i>Liverpool</i>	Mr. M.J. Leitch, <i>M.I.T.</i>
Mr. C.G. Andersson, <i>Lund</i>	Dr. G. Lhersonneau, <i>Leuven</i>
Mr. X.A. Aslanoglou, <i>Demokritos</i>	Mr. C.J. Lister, <i>Liverpool</i>
Mr. S. Baird, <i>Birmingham</i>	Mr. M.N. Martins, <i>Sao Paulo</i>
Mr. A. Bockisch, <i>Germany</i>	Mr. M. Modarres, <i>Manchester</i>
Mr. J.M. Cavedon, <i>Saclay</i>	Professor G.M. Morrison, <i>Birmingham</i>
Mr. G.L. Cleland, <i>Glasgow</i>	Dr. D. Muller, <i>Princeton</i>
Mr. M.C. Cooke, <i>Harwell</i>	Mr. J. Okolowicz, <i>Poland</i>
Dr. T.M. Cormier, <i>Stony Brook</i>	Dr. R.O. Owens, <i>Glasgow</i>
Dr. J. Cugnon, <i>Liege</i>	Dr. A. Pantaleo, <i>Bari</i>
Mr. R.P. DeVito, <i>East Lansing</i>	Dr. G. Pantaleo D'Erasmus, <i>Bari</i>
Mr. K.S. Dhuga, <i>Birmingham</i>	Dr. Phan-Xuan-Ho, <i>Saclay</i>
Dr. M. Durand, <i>Grenoble</i>	Dr. S. Plattard, <i>Bruyeres-le-Chatel</i>
Dr. M. Faber, <i>Wien</i>	Mr. Polls-Marti, <i>Granada</i>
Dr. L.W. Fagg, <i>Washington D.C.</i>	Mr. G. Proudfoot, <i>Oxford</i>
Dr. H. Ferdinande, <i>Ghent</i>	Dr. R.M. Ronningen, <i>Heidelberg</i>
Dr. D.J.S. Findlay, <i>Glasgow</i>	Dr. J. Sanchez-Dehesa, <i>Julich</i>
Mr. E. Flerackers, <i>Limburgs</i>	Dr. A.M. Saruis, <i>Bologna</i>
Mr. A.G. Flowers, <i>Edinburgh</i>	Dr. R. Schwentker, <i>Mainz</i>
Dr. G. Fratamico, <i>Bologna</i>	Mr. F. Sever, <i>Ljubljana</i>
Dr. K. Fukuda, <i>Japan</i>	Dr. P. Singer, <i>Heidelberg</i>
Dr. Y.R. Gaillard, <i>France</i>	Dr. E. Spamer, <i>Darmstadt</i>
Miss S. Gary, <i>Saclay</i>	Dr. F. Stancu, <i>Leige</i>
Dr. P.D. Giacomo, <i>Frascati</i>	Dr. R.S. Storey, <i>Ottawa</i>
Mr. D.J. Gibson, <i>Glasgow</i>	Dr. H. Thierens, <i>Ghent</i>
Dr. M.D. Glascock, <i>Maryland</i>	Mr. J.A. Tostevin, <i>Guildford</i>
Mr. C.A. Harter, <i>Manchester</i>	Miss S. Turck, <i>Saclay</i>
Dr. H. Jasicek, <i>Wien</i>	Dr. H. Van der Voorde, <i>Leuven</i>
Dr. R. Kamermans, <i>Netherlands</i>	Mr. B.J. Varley, <i>Manchester</i>
Mr. A.M. Klein, <i>Tel-Aviv</i>	Mr. J. Verplancke, <i>Leuven</i>
Mrs. E.A. Knight, <i>Glasgow</i>	Dr. A. Vidal-Quadras, <i>Barcelona</i>
Mr. R. Wadsworth, <i>Liverpool</i>	Dr. A. Wolf, <i>Beer-Sheba</i>
Mr. A.O. Williams, <i>Manchester</i>	Dr. A. Zucchiatti, <i>Genoa</i>





### Key to group photograph

1. A Shotter	29. S Gary	57. X A Aslanoglou
2. I Crawford	30. P Anderson	58. M S Afghani
3. J Speth	31. M N Martins	59. A M Klein
4. H C Pauli	32. A M Sarius	60. J A Tostevin
5. A M Green	33. R Wadsworth	61. B J Varley
6. W Greiner	34. C J Lister	62. P Martin
7. D F Jackson	35. Y R Gaillard	63. J M Cavedon
8. J M Reid	36. R Schwentker	64. D J S Findlay
9. J B A England	37. A Zucchiatti	65. H. Jasicek
10. M H MacFarlane	38. L W Fagg	66. A G Flowers
11. S Penner	39. E Spamer	67. H Ferdinande
12. A Watt	40. R Kamermans	68. J Larysz
13. R R Whitehead	41. M J Leitch	69. Phan-Xuan-Ho
14. S J. Hall	42. C G Anderson	70. M Faber
15. K Ledingham	43. S Baird	71. H Thierens
16. G Lhersonneau	44. J Cugnon	72. T M Cormier
17. A Al-Naser	45. D J Gibson	73. R M Ronningen
18. M Modarres	46. K S Dhuga	74. S Plattard
19. D Muller	47. R P de Vito	75. F Sever
20. A Wolf	48. R S Storey	76. G L Cleland
21. G Fratamico	49. A Bockisch	77. J Okolowicz
22. P Singer	50. C A Harter	78. G Proudfoot
23. N Pacholek	51. M C Cooke	79. K Fukuda
24. P Di Giacomo	52. A Vidal-Quadras	80. J M Irvine
25. M da C Abreu	53. A Pantaleo	81. H J Specht
26. G D'Erasmo	54. A Polls-Marti	82. D K Scott
27. S Turck	55. M D Glascock	83. E A Knight
28. F Stancu	56. J Sanchez-Dehesa	



## DIRECTOR'S PREFACE

The Eighteenth Scottish Universities Summer School in Physics was held in the University of St. Andrews from 31st July - 20th August, 1977.

It is twelve years since the Scottish Universities' Summer School in Physics was last devoted to the subject of Nuclear Physics and the school reflected the many advances, both in theoretical understanding and experimental technique, which have taken place in the intervening years. We felt it appropriate to pay particular attention to the developments in heavy ion physics and electromagnetic interactions with nuclei.

We were fortunate to be able to call on a body of lecturers who not only have made considerable personal contributions to these advances but who are also noted for their lecturing skills. Their enthusiasm for their subject was readily transmitted to the students resulting in a very successful school. These Proceedings I believe will prove a significant contribution to the literature on Nuclear Physics and will help to spread the benefits of the school to a larger audience than those who were able to attend.

The School was sponsored by and had the support of the eight Scottish Universities and the Scientific Affairs Division of NATO.

The participants, the lecturers and their families were housed in David Russell Hall and we are greatly indebted to the Warden, Dr. C. Ingram and the Domestic Bursar, Mrs. Ferguson, for the excellent organisation, catering and other arrangements. The lectures and seminars were held in the Physics Building of the University and it is a pleasure to acknowledge the kind assistance and hospitality accorded us by Professor J.F. Allen and his staff. In particular we are grateful to Dr. D.M. Finlayson and Dr. N. McGill.

Finally I wish to acknowledge the contributions made by all those who helped to organise and run the School. Ian Crawford, as Secretary, handled all the correspondence for School before, after and during our stay in St. Andrews. Sam Hall and Max Irvine edited a volume that at times threatened to grow without limit. Rex Whitehead managed to balance the books. Ken Ledingham organised the social activities while my wife Jean arranged the ladies programme. Bob Owen, Alan Shotter and Sandy Watt fetched and carried and generally attended to the hundred and one duties which were required for the smooth running of the School.

## EDITORS' NOTE

The articles in this volume have been prepared by the authors and are based closely on the lectures presented at the Summer School. Editing has been minimal, directed towards correcting errors and achieving some degree of uniformity of notation throughout the volume.

In addition to the formal lectures a number of informal seminars on Mesonic Effects in Nuclei, Gas Filled Detectors, Giant Dipole Resonances, Heavy Ion Potentials, Fission, C.W. Accelerators, Giant Multipole Resonances and Photonuclear Reactions were held but these are not recorded in these Proceedings.

We are grateful to J. Spark, T. McQueen and B. McAndie for technical assistance during the period of the School and to Norma Pacholek, Heather Kimber and Pat Anderson for secretarial assistance throughout the preparation of the Proceedings.

Finally, we should like to express our gratitude for the unprecedented co-operation which we received from our Lecturers.

## CONTENTS

### MICROSCOPIC MODELS OF NUCLEI

M.H. MacFARLANE

1. Shell Theory and Single-Particle Excitations	1
1.1 <i>Introduction</i>	1
1.2 <i>The Phenomenological Single-Particle Potential</i>	3
1.3 <i>Velocity-Dependence, Hartree-Fock and the Harmonic-Oscillator Approximation</i>	9
1.4 <i>Single-Particle Excitations; Single-Hole Excitations and Nuclear Spectra</i>	12
1.5 <i>Theory of Angular Momentum - Notation and Wigner-Eckart Theorem.</i>	17
1.6 <i>Fractional Parentage and Spectroscopic Factors</i>	22
2. Many-Body Theory and Phenomenology in the Derivation of the Shell-Model Hamiltonian	28
2.1 <i>Model Spaces and Effective Interactions in Nuclear Shell Theory</i>	28
2.2 <i>Nuclear Matter, the Brueckner G-matrix and why the Shell-Model works</i>	33
2.3 <i>Brueckner-Hartree-Fock (BHF) Calculations of Double Closed Shell Nuclei</i>	46
2.4 <i>Microscopic Calculations of the Shell-Model Effective Interaction</i>	51
2.5 <i>Phenomenological Shell-Model Effective Interactions</i>	66
2.6 <i>Many Particle Contributions to the Effective Interaction</i>	75
2.7 <i>Summary - Semi-Realistic Interactions</i>	77

3.	Calculational Techniques in Many-Particle Shell Theory	78
3.1	<i>Historical Background and the Alternative Strategies</i>	78
3.2	<i>The Traditional Strategy and Multi-Shell Spectroscopy</i>	79
3.3	<i>The Computer-Oriented Strategy and the Lanczos Algorithm</i>	85
3.4	<i>The Centre-of-Mass Problem in Nuclear Shell Theory</i>	92
3.5	<i>The State of the Art - Assessment and Future Prospects</i>	94
	References	96

## THE NEW GIANT RESONANCES

J. SPETH

1.	Introduction	101
1.1	<i>Liquid Drop Model</i>	102
1.2	<i>Harmonic Oscillators</i>	104
1.3	<i>Experimental Situation of the GQR</i>	105
2.	Random-Phase Approximation	108
2.1	<i>Basic Formulas</i>	108
2.2	<i>Different Numerical Approaches</i>	110
	a) <i>Shell-Model R.P.A. Calculations</i>	110
	b) <i>Self-consistent R.P.A. Calculations</i>	110
3.	1p-1h R.P.A. Results	111
4.	Spreading Widths of GQR in $^{16}\text{O}$ and $^{208}\text{Pb}$	116
4.1	<i>Structure of the GQR in <math>^{16}\text{O}</math></i>	117
4.2	<i>Fine Structure of the GQR in <math>^{16}\text{O}</math> and <math>^{208}\text{Pb}</math></i>	118
5.	Magnetic Resonances and the Spin-Dependent Part of the p-h Interaction	122
5.1	<i>The Low-Lying Giant M1 Resonances</i>	123
5.2	<i>The High-Lying Giant M1 Resonances</i>	126
	References	130

## SHORT RANGE CORRELATIONS DUE TO ISOBAR CONFIGURATIONS

A.M. GREEN

1.	Introduction	133
2.	The Importance of Isobars	134

3.	The Transition Potentials	136
4.	Generating Isobar Configurations	139
5.	A Recent Development	142
6.	Isobar Configurations in Few Nucleon Systems	147
6.1	<i>Isobar Components in the Deuteron</i>	147
6.2	<i>Isobar Components in <math>^3\text{He}</math></i>	149
6.3	<i>The Effect of Isobar Configurations</i>	149
7.	Conclusions	153
	References	156

## REACTION THEORY

D.F. JACKSON

1.	Introduction	159
2.	Theoretical Techniques	160
2.1	<i>Partial Wave Methods</i>	160
2.2	<i>Green's Function Techniques</i>	162
2.3	<i>Approximate Methods</i>	164
2.4	<i>Multiple Scattering Expansions</i>	167
2.5	<i>Two-Potential Formulae</i>	169
2.6	<i>Theory of the Generalized Optical Potential and Compound Resonances</i>	170
3.	Applications and Interpretation	174
3.1	<i>Folding Models for Optical Potentials</i>	174
3.2	<i>A Resonance Reaction - Alpha-Decay</i>	178
3.3	<i>Antisymmetrisation in Nuclear Scattering</i>	182
3.4	<i>Heavy Ion Peripheral Collisions</i>	185
4.	Outstanding Problems	188
	References	190

## EXPERIMENTAL TECHNIQUES IN NUCLEAR PHYSICS

J.B.A. ENGLAND

1.	General Instrumentation	193
1.1	<i>Introduction</i>	193

1.2	<i>Ion Sources</i>	195
1.3	<i>Accelerators</i>	198
1.4	<i>Beam Transport Systems</i>	200
1.5	<i>Target Effects</i>	202
1.6	<i>Beam Measuring Systems</i>	204
1.7	<i>Conclusions</i>	205
2.	<b>Charged Particle Detection I</b>	205
2.1	<i>Introduction</i>	205
2.2	<i>Energy Loss, Particle Range and Statistics</i>	206
2.3	<i>Multiwire Proportional Chambers</i>	212
2.4	<i>Conclusion</i>	214
3.	<b>Charged Particle Detection II</b>	214
3.1	<i>Introduction</i>	214
3.2	<i>MWPC for Nuclear Structure Research</i>	214
3.3	<i>Position Sensitive Proportional Counters</i>	218
3.4	<i>Parallel Plate Chambers</i>	220
3.5	<i>Drift Chambers</i>	221
3.6	<i>Multiparameter Detectors</i>	223
3.7	<i>Conclusion</i>	225
4.	<b>High Resolution Systems I</b>	225
4.1	<i>Introduction</i>	225
4.2	<i>Semiconductor Detectors for Charged Particles</i>	226
4.3	<i>Position Sensitive Semiconductor Detectors</i>	230
4.4	<i>Si(Li), Ge(Li) and Intrinsic Germanium Detectors</i>	233
4.5	<i>Fast Timing Systems</i>	235
4.6	<i>Conclusion</i>	238
5.	<b>High Resolution Systems II</b>	238
5.1	<i>Introduction</i>	238
5.2	<i>Higher Order Focussing Fields</i>	239
5.3	<i>Kinematic Correction</i>	241
5.4	<i>Spectrometer Systems with Single Dipole Elements</i>	243
5.5	<i>Spectrometers with Multiple Dipole Elements</i>	248
5.6	<i>Conclusion</i>	253
6.	<b>Identification Methods</b>	253
6.1	<i>Introduction</i>	253

6.2	<i>Time-of-Flight Systems for Charged Particles</i>	254
6.3	<i>Single Detector Systems</i>	257
6.4	<i>Particle Identification by Energy Loss Telescopes</i>	258
6.5	<i>Magnetic Spectrometers as Particle Identifiers</i>	260
6.6	<i>Velocity Filters and On-Line Mass Spectrometers</i>	261
6.7	<i>Enhancement of Gamma Rays from High Spin States</i>	262
6.8	<i>Problems and Questions</i>	263
6.9	<i>Conclusion</i>	263
	<b>References</b>	264

## ELECTRON SCATTERING

S. PENNER

1.	<b>Introduction</b>	269
1.1	<i>General Overview</i>	269
1.2	<i>Historical Development</i>	271
2.	<b>Theory</b>	275
2.1	<i>The General Born Approximation Cross Section</i>	275
2.2	<i>Coulomb Distortion</i>	279
2.3	<i>Higher Order Corrections</i>	282
2.4	<i>Radiative Tails</i>	286
2.5	<i>Thick Target Effects</i>	287
3.	<b>Experimental Considerations</b>	288
3.1	<i>Magnetic Spectrometers</i>	288
3.2	<i>Energy Loss Systems</i>	290
3.3	<i>Detector Systems</i>	292
3.4	<i>Energy Calibration</i>	295
3.5	<i>Beam Charge Measurement</i>	297
3.6	<i>Geometry</i>	298
4.	<b>Elastic Scattering</b>	299
4.1	<i>Interpretation of Experimental Data</i>	299
4.2	<i>Charge Scattering</i>	302
4.3	<i>"Model Independent Analysis"</i>	304
4.4	<i>Muonic X-ray Data</i>	307
4.5	<i>Magnetic Elastic Scattering</i>	308



5.	Inelastic Scattering	310
5.1	<i>Nuclear Spectroscopy by Inelastic Electron Scattering</i>	310
5.2	<i>Scattering from Discrete Nuclear States</i>	314
5.3	<i>Continuum Scattering</i>	319
6.	Coincidence Experiments	322
6.1	<i>General Considerations</i>	322
6.2	<i>Quasielastic Scattering</i>	326
6.3	<i>Future Coincidence Possibilities</i>	329
	References	332

## COLLECTIVE NUCLEAR MODELS AND THEIR APPLICATIONS

P.O. HESS AND W. GREINER

1.	Collective Model for Low-Energy Spectra	339
1.1	<i>The Quadrupole Co-ordinate</i>	341
1.2	<i>The Potential Energy Surface (PES)</i>	344
1.3	<i>The Operator of the Kinetic Energy</i>	347
1.4	<i>The Hamiltonian</i>	348
1.5	<i>The Eigenstates of the Five-Dimensional Oscillator</i>	349
1.6	<i>Diagonalisation of H and Convergence of the Numerical Procedure</i>	351
1.7	<i>Examples of Spectra</i>	355
1.8	<i>Summary</i>	371
2.	Improvement of the Gneuss-Greiner Model	371
2.1	<i>The Hamiltonian of the Five-Dimensional Oscillator in <math>\beta\gamma</math>-Representation</i>	372
2.2	<i>Eigenfunctions of the Hamiltonian</i>	373
2.3	<i>New Terms of the Potential</i>	376
2.4	<i>Summary</i>	379
3.	Coupling of Giant Resonance States with the Low-Energy Spectra	379
3.1	<i>The Hamiltonian of the Dynamic Collective Model</i>	380
3.2	<i>Hydrodynamical Model for GRS</i>	380
3.3	<i>The Interaction Operator <math>H_{DQ}</math></i>	384
3.4	<i>The Basis States for Diagonalization</i>	386
3.5	<i>The Dipole-Operator and the <math>\gamma</math>-Absorption Cross-Section</i>	386
3.6	<i>Results</i>	387