



**PROGRESS**  
**IN**  
**COSMIC RAY PHYSICS**

**EDITED BY**

**J. G. WILSON, M. A., Ph. D., F. Inst. P.**

**UNIVERSITY OF MANCHESTER**

**CONTRIBUTORS:**

**U. CAMERINI**

**L. MICHEL**

**G. PUPPI**

**W. O. LOCK**

**B. PETERS**

**N. DALLAPORTA**

**D. H. PERKINS**

**H. V. NEHER**

**E. P. GEORGE**

**C. C. BUTLER**

**H. ELLIOT**

**1952**

**NORTH-HOLLAND PUBLISHING COMPANY, AMSTERDAM**  
**INTERSCIENCE PUBLISHERS, INC. NEW YORK**

## PREFACE

"Progress in Cosmic Ray Physics" is intended to provide a series of reviews covering, in particular, those aspects of the physics of cosmic radiation in which advances of broad significance are now being made.

It is a characteristic of cosmic ray physics that in spite of the extensive specialized research of the last five years, the separation of the subject into more or less independent topics has not gone very far. The main geophysical investigations remain among the most fruitful sources in which hitherto unknown interactions are identified, while the interpretation of these large scale phenomena must essentially depend on a detailed understanding of the single nucleon-nucleon encounter. Interrelations between the various geophysical features are still closer, while neither the relevance of the broad conclusions of fundamental particle theory to the experimental pursuit of these particles, nor the importance to the theorist of a balanced assessment of the changing experimental position, need be stressed. Up to date surveys of the state of knowledge in the various branches of the subject are accordingly likely to be of particular value to active workers on specialized problems, and the reviews of this volume, which in general give the standpoint of the early months of 1951, have this requirement in view. They aim also to cover the much wider need of workers in related subjects, particularly in nuclear physics and in astrophysics, for information about current trends in cosmic ray work.

It is not possible, in a single volume of moderate size, to survey all the main lines of cosmic ray investigations, and rather drastic selection has been necessary. It is hoped, however, to cover other subjects in later volumes, where further reports on topics in rapid development would also appear.

I am grateful to the various authors and to the publishers, for the very active co-operation which has made quick publication possible.

J. G. WILSON

*Manchester, September 1951*

*Sole Distributors for U.S.A.*  
*Interscience Publishers, Inc. New York*

PRINTED IN THE NETHERLANDS  
DRUKKERIJ HOLLAND N.V., AMSTERDAM

# CONTENTS

## CHAPTER I

### THE ANALYSIS OF ENERGETIC NUCLEAR ENCOUNTERS OCCURRING IN PHOTOGRAPHIC EMULSIONS

INTRODUCTION . . . . .	3
------------------------	---

#### PART I

#### RADIATIVE COLLISIONS

1. MESON PRODUCTION IN NUCLEON-NUCLEON COLLISIONS	5
1.1 Theories . . . . .	5
1.2 Experimental methods; nomenclature and technique . . .	6
1.3 Yield curve for mesons . . . . .	7
1.4 The production of neutral mesons . . . . .	12
1.5 Comparison of multiplicity — primary energy relationship with theory . . . . .	13
1.6 Variation of $N_h$ and $N_g$ with primary energy and multiplicity	16
2. MESON-NUCLEON INTERACTION . . . . .	18
2.1 The collision mean free path . . . . .	18
2.2 Stars produced by identified $\pi$ -mesons . . . . .	20
2.3 The interactions of $\pi$ -mesons of energy greater than 1 BeV	21
2.4 Conclusions . . . . .	21
3. PROPERTIES OF THE SHOWER PARTICLES . . . . .	22
3.1 Lorentz transformation to centre of mass system (multiple theory) . . . . .	22
3.2 Energy and angular distributions of the shower particles . .	23
3.3 Interaction of the shower particles with the nucleus . . .	29
4. INDIVIDUAL HIGH ENERGY EVENTS . . . . .	30
4.1 Stars produced by neutrons and singly charged primary particles . . . . .	30
4.2 Stars produced by fast $\alpha$ -particles . . . . .	32
5. CONCLUSIONS . . . . .	32

#### PART II

#### ELASTIC COLLISIONS

6. INTRODUCTION . . . . .	34
---------------------------	----

7. FREQUENCY, ENERGY AND ANGULAR DISTRIBUTION OF FAST NUCLEONS (GREY TRACKS) . . . . .	34
7.1 Frequency of grey tracks . . . . .	34
7.2 Energy distribution of protons producing grey tracks . . . . .	35
7.3 Angular distribution of grey tracks . . . . .	36
7.4 Proportion of grey and black tracks . . . . .	37
8. FREQUENCY, ENERGY AND ANGULAR DISTRIBUTION OF SLOW PARTICLES (BLACK TRACKS); THE EVAPORATION PROCESS . . . . .	38
8.1 Introduction . . . . .	38
8.2 Energy distribution of low energy protons . . . . .	40
8.3 Energy distribution of low energy $\alpha$ -particles . . . . .	44
8.4 Angular distribution of low energy protons . . . . .	46
8.5 Angular distribution of low energy $\alpha$ -particles . . . . .	47
8.6 Emission probabilities for various types of particles . . . . .	48
8.7 Relation between prong number and thermal excitation energy . . . . .	49
9. EMISSION OF HEAVY FRAGMENTS IN STARS . . . . .	51
9.1 Frequency of fragment emission . . . . .	51
9.2 Angular distribution of fragments . . . . .	53
9.3 Emission of low energy fragments (less than 4 MeV per nucleon) . . . . .	54
9.4 Emission of high energy fragments (more than 4 MeV per nucleon) . . . . .	55
10. CONCLUSIONS . . . . .	56
11. OUTSTANDING PROBLEMS . . . . .	57
ACKNOWLEDGEMENTS . . . . .	58
REFERENCES . . . . .	59

## CHAPTER II

### UNSTABLE HEAVY COSMIC RAY PARTICLES

INTRODUCTION . . . . .	65
------------------------	----

## PART I

### THE DECAY OF NEUTRAL V-PARTICLES

1. THE FIRST NEUTRAL V-SHAPED TRACK . . . . .	67
---	----

2. INVESTIGATIONS OF V-SHAPED TRACKS . . . . .	68
2.1 Experimental arrangements used for the detection of neutral V-shaped tracks . . . . .	68
2.2 Statistical data . . . . .	70
2.3 The source of the neutral V-shaped tracks . . . . .	73
3. THE NATURE OF THE SECONDARY PARTICLES . . . . .	73
3.1 Heavily-ionizing secondary particles . . . . .	73
3.2 The penetrating properties of the secondary particles . . . . .	78
3.3 The differential momentum spectrum of the secondary particles . . . . .	79
4. POSSIBLE EXPLANATIONS OF THE NEUTRAL V-SHAPED TRACKS . . . . .	82
4.1 Interactions in the gas of the cloud chamber . . . . .	82
4.2 Large-angle single scattering of particles in the gas of the cloud chamber . . . . .	85
5. SUGGESTED DECAY PROCESSES . . . . .	85
5.1 The number of secondary particles . . . . .	85
5.2 Possible two-particle decay schemes . . . . .	86
6. MASS DETERMINATIONS . . . . .	89
6.1 The decay of $V_1^0$ -particles into protons and $\pi$ -mesons . . . . .	89
6.2 The decay of $V_2^0$ -particles into two $\pi$ -mesons . . . . .	91
7. THE DYNAMICS OF DECAY SCHEMES WITH TWO SECONDARY PARTICLES . . . . .	93
7.1 The dynamics of the decay scheme: $V_1^0 \rightarrow p^+ + \pi^-$ . . . . .	93
7.2 The dynamics of the decay scheme: $V_2^0 \rightarrow \pi^+ + \pi^-$ . . . . .	98
8. THE MEAN REST LIFETIME OF NEUTRAL V-PARTICLES	101
9. CONCLUSIONS . . . . .	101

## PART II

### THE DECAY OF HEAVY CHARGED PARTICLES

10. THE DECAY OF $\tau$ -MESONS . . . . .	105
11. THE DECAY OF CHARGED V-PARTICLES . . . . .	109
11.1 The first charged V-shaped track . . . . .	109
11.2 The statistical data on charged V-shaped tracks . . . . .	109
11.3 The explanation of the charged V-shaped tracks . . . . .	110
11.4 The nature of the secondary particles of charged V-particles	114

11.5	The mass of the charged V-particles . . . . .	116
11.6	The mean rest life-time of charged V-particles . . . . .	120
12.	CONCLUSIONS . . . . .	121
	ACKNOWLEDGEMENTS . . . . .	122
	REFERENCES . . . . .	123

## CHAPTER III

### COUPLING PROPERTIES OF NUCLEONS, MESONS AND LEPTONS

INTRODUCTION . . . . .	127
1. THE PHYSICS OF PARTICLES . . . . .	127
1.1 Experimental data . . . . .	128
1.2 Theoretical methods . . . . .	129
1.3 The conservation laws . . . . .	131
1.4 Coupling between fields . . . . .	133
1.5 Couplings commonly used . . . . .	136
1.6 Couplings not commonly used . . . . .	139
1.7 Units . . . . .	141
1.8 Isotopic variable . . . . .	141
1.9 Furry's theorem . . . . .	142
1.10 Equivalence theorem, radiative corrections, renormalization and regularization . . . . .	144
2. $\pi$ -MESONS AND HEAVIER MESONS . . . . .	145
2.1 Nuclear forces . . . . .	145
2.2 The nature of the $\pi^0$ -meson . . . . .	147
2.3 The nature of the $\pi^\pm$ -meson . . . . .	149
2.4 Are $\pi^0$ and $\pi^\pm$ mesons symmetrical pseudoscalar mesons? . . . . .	151
2.5 Neutral V-mesons . . . . .	153
2.6 Heavier charged mesons, V and $\tau$ . . . . .	155
3. INTERACTION BETWEEN FOUR FERMIONS . . . . .	159
3.1 The neutrino . . . . .	159
3.2 $\mu$ -meson decay . . . . .	161
3.3 The radioactivity of the neutron . . . . .	163
3.4 Nature of the coupling of $\beta$ -radioactivity . . . . .	166
3.5 The capture of $\mu$ -mesons by nuclei . . . . .	172
3.6 Universal direct coupling between four fermions . . . . .	174



4. POSSIBLE COUPLING SCHEMES . . . . .	176
4.1 Coupling scheme (1) . . . . .	176
4.2 Coupling scheme (2): an alternative to scheme (1) . . . . .	179
4.3 Is direct coupling necessary for $\beta$ -radioactivity? . . . . .	179
4.4 Summary . . . . .	181
5. CONCLUSION . . . . .	182
ACKNOWLEDGEMENTS . . . . .	184
REFERENCES . . . . .	185

## CHAPTER IV

### THE NATURE OF PRIMARY COSMIC RADIATION

INTRODUCTION . . . . .	193
1. THE STUDY OF HEAVY PRIMARY PARTICLES IN NUCLEAR EMULSIONS . . . . .	195
1.1 Tracks produced by heavy nuclei . . . . .	195
1.2 Charge determination of heavy primary nuclei . . . . .	197
2. NUCLEAR INTERACTIONS AND ENERGY MEASUREMENTS . . . . .	202
2.1 Different types of nuclear interaction . . . . .	202
2.2 Mean free path for nuclear collisions . . . . .	209
2.3 Energy determination for non-relativistic nuclei . . . . .	210
2.4 Energy determination for relativistic nuclei . . . . .	212
3. THE FLUX AND ENERGY SPECTRUM OF PRIMARY COSMIC RAY NUCLEI . . . . .	216
3.1 The flux of primary $\alpha$ -particles . . . . .	218
3.2 The flux of primary nuclei of charge $Z > 2$ . . . . .	221
3.3 The low energy cut-off for heavy primary nuclei . . . . .	224
3.4 Time fluctuations in the flux of heavy nuclei . . . . .	225
3.5 The energy spectrum of primary cosmic rays . . . . .	225
4. THE CHEMICAL COMPOSITION OF PRIMARY COSMIC RADIATION . . . . .	228
4.1 The charge spectrum between latitudes $\lambda = 55^\circ$ and $\lambda = 30^\circ$ . . . . .	228
4.2 Comparison of the cosmic abundance of elements with their abundance in primary cosmic rays . . . . .	231
5. THE COMPOSITION OF PRIMARY COSMIC RADIATION AND THE PROBLEM OF ITS ORIGIN . . . . .	233
REFERENCES . . . . .	241

## CHAPTER V

## RECENT DATA ON GEOMAGNETIC EFFECTS

INTRODUCTION . . . . .	245
1. AN OUTLINE OF THE THEORY OF GEOMAGNETIC EFFECTS . . . . .	246
1.1 The earth's magnetic field . . . . .	246
1.2 Application of Liouville's theorem . . . . .	247
1.3 Units of energy and momentum . . . . .	247
1.4 Application of Störmer's theory . . . . .	248
1.5 Modifications to Störmer's theory . . . . .	249
1.6 Corrections for eccentricity of dipole . . . . .	251
1.7 Definition of geomagnetic effects . . . . .	253
2. COSMIC RAYS IN THE ATMOSPHERE . . . . .	254
2.1 Units of cosmic ray intensity . . . . .	254
2.2 Relation of intensity in the atmosphere to that above the atmosphere . . . . .	255
2.3 Are there any primary electrons in cosmic rays? . . . . .	256
2.4 Correlation between measurements taken with ionization chambers and counter telescopes . . . . .	256
3. DATA ON GEOMAGNETIC EFFECTS . . . . .	262
3.1 Introduction . . . . .	262
3.2 Description of the apparatus . . . . .	263
3.3 Experiments performed . . . . .	266
3.4 Internal calibrations . . . . .	267
3.5 Corrections to the telescope readings . . . . .	268
3.6 Reduction to absolute values . . . . .	271
3.7 Experimental results . . . . .	272
4. CORRELATION OF GEOMAGNETIC EFFECTS . . . . .	288
4.1 Introduction . . . . .	288
4.2 Correlation of latitude effect and zenith angle effect with the calculations of VALLARTA <i>et al.</i> . . . . .	289
4.3 Correlation of azimuthal effect with zenith angle effect at the equator . . . . .	294
4.4 Correlation of latitude, zenith angle and longitude effects . . . . .	295
4.5 Summary of correlation of geomagnetic effects . . . . .	296
5. ENERGY DISTRIBUTION OF THE PRIMARY RADIATION . . . . .	297
5.1 Introduction . . . . .	297
5.2 Normalization of counter telescope curves . . . . .	297
5.3 Empirical relations . . . . .	301
5.4 Consequences of the above distribution of cosmic ray energy . . . . .	303

6. SOME CONCLUSIONS ON THE GROSS BEHAVIOUR OF COSMIC RAYS IN THE ATMOSPHERE . . . . .	304
6. 1 Introduction . . . . .	304
6. 2 Absorption in lead as a function of minimum momentum of the primaries . . . . .	304
6. 3 Multiplicity of charged particles . . . . .	306
6. 4 Consequences of dependence of multiplicity on energy of the primaries . . . . .	311
7. SUMMARY . . . . .	311
REFERENCES . . . . .	313

## CHAPTER VI

### THE EQUILIBRUM OF THE COSMIC RAY BEAM IN THE ATMOSPHERE

INTRODUCTION . . . . .	317
1. THE PRIMARY COMPONENT AT THE TOP OF THE ATMOSPHERE . . . . .	317
1. 1 Vertical data . . . . .	318
1. 2 Secondary processes and asymmetries . . . . .	320
1. 3 The primary spectrum . . . . .	322
1. 4 Discussion on the hypothesis of primary electrons . . . . .	324
1. 5 Discussion on the hypothesis of negative primaries . . . . .	326
1. 6 Heavy nuclei in the primary radiation . . . . .	327
2. COSMIC RADIATION UNDERGROUND . . . . .	330
3. COSMIC RAYS IN THE ATMOSPHERE . . . . .	332
3. 1 Experimental data at sea-level . . . . .	333
4. THE $\mu$ -COMPONENT . . . . .	336
4. 1 Intensity-height distribution . . . . .	336
4. 2 The spectrum at sea-level . . . . .	339
4. 3 The positive excess . . . . .	342
4. 4 Asymmetries of the positive excess . . . . .	347
5. THE ELECTRON-PHOTON COMPONENT . . . . .	348
5. 1 The total intensity-height distribution . . . . .	349
5. 2 The latitude effect . . . . .	351
5. 3 The energy spectrum; the ratio of electrons to photons . . . . .	351
6. THE N-COMPONENT . . . . .	352
6. 1 Absorption and latitude effect . . . . .	354

6.2	Absolute intensity of the nucleonic component . . . . .	357
6.3	The spectrum of the nucleonic component . . . . .	359
6.4	The ratio of neutrons to protons . . . . .	361
7.	THE GENETIC RELATION . . . . .	363
8.	HIGH ENERGY EVENTS IN THE N-COMPONENT . . . . .	364
8.1	Multiple and plural processes . . . . .	365
8.2	Diffusion of the high energy N-component . . . . .	366
9.	THE $\pi$ -MESONS . . . . .	367
9.1	The generation spectrum of charged $\pi$ -mesons . . . . .	368
9.2	Relation between the spectra of $\pi$ -mesons and $\mu$ -particles . . . . .	370
9.3	Diffusion equation for $\pi$ -mesons . . . . .	370
9.4	Neutral $\pi^0$ -mesons . . . . .	372
9.5	$\tau$ and V-particles . . . . .	373
10.	LOW ENERGY EVENTS IN THE N-COMPONENT . . . . .	373
10.1	Equilibrium between stars and neutrons . . . . .	375
11.	EXTENSIVE AIR SHOWERS . . . . .	380
12.	ENERGY BALANCE OF THE COSMIC RAY BEAM . . . . .	380
12.1	Flux measurements . . . . .	381
12.2	Ratio between neutral and charged $\pi$ -mesons . . . . .	384
12.3	Variation with energy of the absorption length of the N-component . . . . .	386
	ACKNOWLEDGEMENTS. . . . .	387
	REFERENCES . . . . .	388

## CHAPTER VII

### OBSERVATIONS OF COSMIC RAYS UNDERGROUND AND THEIR INTERPRETATION

	INTRODUCTION . . . . .	395
1.	THE DEPTH-INTENSITY RELATION: ABSORPTION MEASUREMENTS . . . . .	395
1.1	Depth-intensity relation, experimental . . . . .	395
1.2	Absorption measurements . . . . .	398
1.3	Angular distribution of the penetrating radiation . . . . .	401
1.4	Depth-intensity relation, corrected values . . . . .	402
2.	CLOUD CHAMBER EVIDENCE CONCERNING THE NATURE OF THE RADIATION . . . . .	403

2.1	Observations at moderate depths, 20—60 m. . . . .	403
2.2	Observations at great depths . . . . .	407
3.	THE DEPTH-INTENSITY RELATION: THEORETICAL . . .	408
3.1	Energy losses of $\mu$ -mesons . . . . .	408
3.2	The range-energy relation for energetic $\mu$ -mesons . . . . .	412
3.3	The energy spectrum at sea-level . . . . .	414
3.4	The influence of $\pi$ -meson interactions . . . . .	416
4.	TIME VARIATIONS; TEMPERATURE COEFFICIENTS . . .	418
4.1	The observations of Rau . . . . .	418
4.2	The observations of MacAnuff . . . . .	420
4.3	Comparison of observations of Rau and MacAnuff . . . . .	424
5.	STARS AND SLOW MESONS IN EMULSIONS . . . . .	424
5.1	Observations of nuclear disintegrations . . . . .	424
5.2	Observations of slow mesons . . . . .	432
5.3	Summary of emulsion work . . . . .	435
6.	SLOW NEUTRONS . . . . .	436
7.	UNDERGROUND SHOWERS . . . . .	438
7.1	Soft showers . . . . .	438
7.2	Penetrating showers . . . . .	441
7.3	Extensive showers . . . . .	443
8.	IONIZATION BURSTS . . . . .	444
9.	PENETRATING PAIRS OF PARTICLES . . . . .	448
	ACKNOWLEDGEMENTS . . . . .	449
	REFERENCES . . . . .	450

## CHAPTER VIII

## TIME VARIATIONS OF COSMIC RAY INTENSITY

INTRODUCTION . . . . .	455
1. VARIATIONS OF ATMOSPHERIC ORIGIN . . . . .	456
1.1 Atmospheric temperature and $\mu$ -meson decay . . . . .	456
1.2 The positive temperature effect . . . . .	458
1.3 The seasonal variation . . . . .	461
2. THE SOLAR DAILY VARIATION . . . . .	466
2.1 Omni-directional measurements . . . . .	466
2.2 Measurements using directional counter arrays . . . . .	472

2.3	The relation between the daily variation and geomagnetic activity . . . . .	477
2.4	The daily variation at great altitudes . . . . .	480
2.5	The semi-diurnal variation . . . . .	481
3.	THE SIDEREAL DAILY VARIATION . . . . .	484
3.1	Galactic rotation and the cosmic ray intensity . . . . .	484
3.2	The separation of solar and sidereal daily variations . . . . .	485
3.3	Recent experimental results . . . . .	488
4.	VARIATIONS ASSOCIATED WITH GEOMAGNETIC AND SOLAR ACTIVITY . . . . .	492
4.1	Magnetic storms and the cosmic ray intensity . . . . .	492
4.2	The 27-day recurrence tendency . . . . .	497
4.3	Increases of intensity associated with solar flares . . . . .	502
APPENDIX. Geographic and geomagnetic coordinates of cosmic ray intensity recording stations . . . . .		511
REFERENCES . . . . .		512
AUTHOR INDEX . . . . .		515
SUBJECT INDEX . . . . .		549

CHAPTER I

**THE ANALYSIS OF ENERGETIC  
NUCLEAR ENCOUNTERS OCCURRING IN  
PHOTOGRAPHIC EMULSIONS**

BY

U. CAMERINI, W. O. LOCK and D. H. PERKINS

*The H. H. Wills Physical Laboratory, University of Bristol*

INTRODUCTION . . . . .	3
------------------------	---

## PART I

### RADIATIVE COLLISIONS

1. MESON PRODUCTION IN NUCLEON-NUCLEON COLLISIONS	5
2. MESON-NUCLEON INTERACTION . . . . .	18
3. PROPERTIES OF THE SHOWER PARTICLES . . . . .	22
4. INDIVIDUAL HIGH ENERGY EVENTS . . . . .	30
5. CONCLUSIONS . . . . .	32

## PART II

### ELASTIC COLLISIONS

6. INTRODUCTION . . . . .	34
7. FREQUENCY, ENERGY AND ANGULAR DISTRIBUTION OF FAST NUCLEONS (GREY TRACKS). . . . .	34
8. FREQUENCY, ENERGY AND ANGULAR DISTRIBUTION OF SLOW PARTICLES (BLACK TRACKS); THE EVAPOR- ATION PROCESS. . . . .	38
9. EMISSION OF HEAVY FRAGMENTS IN STARS. . . . .	51
10. CONCLUSIONS . . . . .	56
11. OUTSTANDING PROBLEMS . . . . .	57
ACKNOWLEDGEMENTS . . . . .	58
REFERENCES . . . . .	59



## INTRODUCTION

With the development of electron-sensitive emulsions, the field of research open to the emulsion technique has been greatly extended, and it has become possible to apply this method, with advantage, to the study of problems which had hitherto been the province of the geiger counter and the cloud chamber.

In particular, the method permits detailed observations on the penetrating showers of particles created in energetic nuclear encounters, and it is the purpose of this article to describe observations made in this field.

Before entering into a detailed discussion of the experimental results relating to penetrating showers, we shall outline the types of interaction which are believed to occur in the nucleon-nucleon encounters. This will be done in the order in which the processes are assumed to occur in the nucleus.

The incident high energy nucleon, which we shall call the primary, makes, within a time of the order of  $10^{-23}$  sec. (the time of traversal of the nucleus) a series of collisions with the individual nucleons of the nucleus; collisions which may either be elastic or radiative. In the latter case various types of quanta may be radiated. It is generally believed that these are  $\pi$ -mesons, and possibly heavier mesons or nucleon pairs, but that direct creation of photons or  $\mu$ -mesons does not occur. At present very little is known about the production of mesons heavier than  $\pi$ -mesons, and we shall therefore limit ourselves to interactions leading to creation of  $\pi$ -mesons only. The radiative processes will be discussed in Part I.

In both elastic and inelastic collisions recoil nucleons will be produced which, together with the primary and any mesons created, can interact further with the nucleus. In this process lower energy nucleons are generated and by further successive encounters these distribute part of their energy through the nucleus, although they will in general escape from it before losing all their kinetic energy. In this way a statistical distribution of energy will be attained in a time large compared with the interval