STRING THEORY AND PARTICLE PHYSICS

String theory is one of the most active branches of theoretical physics, and has the potential to provide a unified description of all known particles and interactions. This book is a systematic introduction to the subject, focused on the detailed description of how string theory is connected to the real world of particle physics.

Aimed at graduate students and researchers working in high-energy physics, it provides explicit models of physics beyond the Standard Model. No prior knowledge of string theory is required as all necessary material is provided in the introductory chapters. The book provides particle phenomenologists with the information needed to understand string theory model building, and describes in detail several alternative approaches to model building, such as heterotic string compactifications, intersecting D-brane models, D-branes at singularities, and F-theory.

LUIS E. IBÁÑEZ is Professor of Theoretical Physics at the Universidad Autónoma de Madrid and member of the Instituto de Física Teórica-UAM/CSIC. One of the world leaders in physics beyond the Standard Model of particle physics, he has made important contributions to the construction of the supersymmetric Standard Model and superstring phenomenology.

ANGEL M. URANGA is Research Professor at the Consejo Superior de Investigaciones Científicas at the Instituto de Física Teórica-UAM/CSIC. He is one of the leading young string theorists working in the construction of models of particle physics, in particular due to his contribution on the use of D-branes to build realistic brane-world models.

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STRING THEORY AND PARTICLE PHYSICS: AN INTRODUCTION TO STRING PHENOMENOLOGY

LUIS E. IBÁÑEZ
Universidad Autónoma de Madrid and Instituto de Física Teórica IFT-UAM/CSIC

ANGEL M. URANGA
Instituto de Física Teórica IFT-UAM/CSIC

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To our families

[. . .] vi el Aleph, desde todos los puntos, vi en el Aleph la tierra, y en la tierra otra vez el Aleph y en el Aleph la tierra [. . .] porque mis ojos habían visto ese objeto secreto y conjetural, cuyo nombre usurpan los hombres, pero que ningún hombre ha mirado: el inconcebible universo.

Excerpt from *El Aleph* by Jorge Luis Borges,

Contents

	Preface		*page* xi
1	**The Standard Model and beyond**		1
	1.1	The Standard Model of particle physics	1
	1.2	Grand Unified Theories	4
	1.3	The SM fine-tuning puzzles	12
	1.4	Extra dimensions	18
2	**Supersymmetry**		25
	2.1	Four-dimensional $\mathcal{N} = 1$ supersymmetry	25
	2.2	SUSY breaking	32
	2.3	$\mathcal{N} = 1$ Supergravity	35
	2.4	Extended supersymmetry and supergravity	37
	2.5	Non-perturbative dynamics in supersymmetric theories	41
	2.6	Low-energy supersymmetry and the MSSM	44
3	**Introduction to string theory: the bosonic string**		62
	3.1	Generalities	63
	3.2	Closed bosonic string	72
	3.3	Open bosonic string	91
	3.4	Unoriented bosonic string theory	97
4	**Superstrings**		103
	4.1	Fermions on the worldsheet	103
	4.2	Type II string theories	104
	4.3	Heterotic string theories	117
	4.4	Type I string theory	126
	4.5	Summary	134
5	**Toroidal compactification of superstrings**		136
	5.1	Type II superstrings	136
	5.2	Heterotic superstrings	141
	5.3	Type I toroidal compactification and D-branes	146

6	**Branes and string duality**		155
	6.1	D-branes in string theory	155
	6.2	Supergravity description of non-perturbative states	165
	6.3	Strings at strong coupling and 10d string duality	168
	6.4	AdS/CFT and gauge/gravity dualities	178
	6.5	Brane–antibrane systems and non-BPS D-branes	180
7	**Calabi–Yau compactification of heterotic superstrings**		185
	7.1	A road map for string compactifications	185
	7.2	Generalities on Calabi–Yau compactification	186
	7.3	Heterotic CY compactifications: standard embedding	199
	7.4	Heterotic CY compactifications: non-standard embedding	206
	7.5	CY compactifications of Hořava–Witten theory	211
8	**Heterotic string orbifolds and other exact CFT constructions**		215
	8.1	Toroidal orbifolds	215
	8.2	Heterotic compactification on toroidal orbifolds	218
	8.3	Non-standard embeddings and Wilson lines	235
	8.4	Asymmetric orbifolds	242
	8.5	The fermionic construction	246
	8.6	Gepner models	252
9	**Heterotic string compactifications: effective action**		264
	9.1	A first look at the heterotic 4d $\mathcal{N} = 1$ effective action	264
	9.2	Heterotic M-theory effective action	272
	9.3	Effective action of orbifold models	273
	9.4	Gauge couplings and Kac–Moody level	280
	9.5	Anomalous $U(1)$s and Fayet–Illiopoulos terms	282
	9.6	T-duality and the effective action	286
	9.7	Orbifold model building revisited	293
	9.8	Higher Kac–Moody level models and string GUTs	296
10	**Type IIA orientifolds: intersecting brane worlds**		298
	10.1	Type II on CY and orientifolding	298
	10.2	Intersecting D6-branes in flat 10d space	302
	10.3	Compactification and an example of a toroidal model	306
	10.4	Introducing O6-planes	314
	10.5	Non-supersymmetric particle physics models	320
	10.6	Supersymmetric particle physics models in $T^6/Z_2 \times Z_2$ orientifolds	325
	10.7	Generalizations and related constructions	329
11	**Type IIB orientifolds**		340
	11.1	Generalities of type IIB orientifold actions	340
	11.2	Type IIB toroidal orientifolds	341
	11.3	D-branes at singularities	356

11.4 Magnetized D-brane models 370
11.5 F-theory model building 381

12 Type II compactifications: effective action 396
12.1 The closed string moduli in type II orientifolds 396
12.2 Kähler metrics of matter fields in toroidal orientifolds 404
12.3 The gauge kinetic function 408
12.4 $U(1)$'s and FI terms 412
12.5 Superpotentials and Yukawa couplings in type II orientifolds 416
12.6 Effective action of an MSSM-like example 426
12.7 Yukawa couplings in local F-theory models 429

13 String instantons and effective field theory 432
13.1 Instantons in field theory and string theory 432
13.2 Fermion zero modes for D-brane instantons 441
13.3 Phenomenological applications 446

14 Flux compatifications and moduli stabilization 455
14.1 Type IIB with 3-form fluxes 455
14.2 Fluxes in type II toroidal orientifolds 467
14.3 D-branes and fluxes 475
14.4 Mirror symmetry, T-duality, and non-geometric fluxes 479
14.5 Fluxes in other string constructions 482

15 Moduli stabilization and supersymmetry breaking in string theory 483
15.1 SUSY and SUSY breaking in string compactifications 483
15.2 SUSY breaking and moduli fixing in heterotic models 485
15.3 SUSY breaking and moduli fixing in type II orientifolds 489
15.4 Soft terms from fluxes in type IIB orientifolds 495
15.5 General parametrization of moduli/dilaton induced SUSY breaking 501
15.6 Modulus/dilaton dominated SUSY breaking spectra and the LHC 510
15.7 Other mediation mechanisms in string theory 515

16 Further phenomenological properties. Strings and cosmology 518
16.1 Scales and unification in string theory 518
16.2 Axions in string theory 528
16.3 R-parity and B/L-violation 531
16.4 Extra $U(1)$ gauge bosons 534
16.5 Strings at the weak scale 540
16.6 Strings and cosmology 543

17 The space of string vacua 558
17.1 General properties of the massless spectrum in string compactifications 558
17.2 The flavour landscape 566

17.3 The flux landscape 570
17.4 Outlook 573

Appendix A **Modular functions** 576

Appendix B **Some topological tools** 579
B.1 Forms and cycles: cohomology and homology 579
B.2 Hodge dual 584
B.3 Application: p-form gauge fields 585
B.4 Homotopy groups 588

Appendix C **Spectrum and charges of a semi-realistic Z_3 heterotic orbifold** 589

Appendix D **Computation of RR tadpoles** 592
D.1 RR tadpoles in type I theory 592
D.2 Tadpoles for T^6/Z_N type IIB orientifolds 595

Appendix E **CFT toolkit** 597
E.1 Conformal symmetry and conformal fields 597
E.2 Vertex operators and structure of scattering amplitudes 599
E.3 Kac–Moody algebras 602
E.4 $\mathcal{N}=2$ superconformal field theories 604
E.5 Rational conformal field theory and simple currents 604

Bibliography 608
References 624
Index 657

Preface

String theory is the leading candidate for a consistent quantum theory of gravity. It has also become a central area of research in mathematical physics, with different additional applications which range from heavy ion physics to condensed matter, cosmology or mathematics. Notwithstanding this, the excitement fostered in 1984 actually came from the coexistence of chiral anomaly free gauge theories and gravity in string theory, raising the expectation of an ultimate unification of Standard Model (SM) and gravitational interactions into a consistent string quantum theory. The enthusiasm was thus motivated by particle physics phenomenological goals.

Since then much effort has been dedicated to explore the possible embedding of the SM of particle physics in string theory, a field commonly known as string phenomenology. However, although there are by now several excellent books introducing the general field of string theory, there is no systematic and detailed coverage of the large body of knowledge accumulated in string phenomenology. This lack has become particularly acute after the duality revolution of 1995, when the advent of D-branes made the string engineering of non-trivial gauge theories more flexible, thus providing new avenues to realize the SM in string theory.

Consequently, and due to the seemingly imposing complexity of string theory, this field has not permeated much to many particle physics phenomenologists and model builders, who feel reluctant to struggle with a jungle of papers and reviews to extract the phenomenological aspects of string theory.

The main purpose of this book is to provide an elementary introduction to string theory, and to string phenomenology, in a systematic and self-contained way. It should be useful to particle phenomenologists and model builders, both senior and fresh. It will also be useful to string theorists interested in learning how (and how far) string theory may reproduce the observed SM physics.

The book has six chapters with introductory material. The first presents a brief summary of the SM structure, its puzzles, and several of its extensions, including Grand Unified Theories and extra dimensions. The second introduces the basic aspects of supersymmetry and its application to particle physics models, most notably the Minimal Supersymmetric

Standard Model (MSSM). These first two chapters serve to fix the notation and introduce concepts, appearing later when building string theory models of particle physics.

Chapters 3 to 6 constitute an introduction to the basics of string theory including the bosonic string (Chapter 3), and the heterotic, type II and type I superstrings (Chapter 4). The simplest toroidal compactification to four dimensions is described in Chapter 5, which also provides a first glimpse of D-branes. Chapter 6 describes D-branes and their role in string theory, as well as the different non-perturbative dualities in the theory. Our presentation in these chapters aims at getting the main physical results in the most comfortable way for the non-initiated, avoiding the machinery of conformal field theory (partly covered in an appendix). These four chapters are self-contained and constitute by themselves an introductory course on string theory, useful also to graduate students searching for a first contact with the formalism of string theory. String theorists acquainted with this material may safely jump over to Chapter 7.

Chapters 7 to 12 give a relatively detailed description of string compactifications giving rise to chiral theories in four dimensions, with emphasis on those with $\mathcal{N} = 1$ supersymmetry and a particle content close to the SM. They include different heterotic constructions, in Chapters 7 and 8, whose low-energy effective action is covered in Chapter 9, as well as type II orientifolds (and M- and F-theory related constructions), in Chapters 10 and 11, with their effective action discussed in Chapter 12. Detailed explicit examples of MSSM-like models are presented for the different compactification methods. The purpose is to enable the reader to obtain the massless spectrum and effective lagrangian of these string constructions, so as to grasp their contact to SM physics.

Chapters 13 and 14 introduce additional ingredients, most notably string instantons and closed string fluxes. Those ingredients give rise to extra contributions to the effective action relevant for aspects like Yukawa couplings, neutrino masses and moduli stabilization. Chapter 15 continues the study of moduli fixing and its interplay with supersymmetry breaking, reaching up to the generation of low-energy supersymmetry breaking masses in MSSM-like models. Further phenomenological issues are discussed in Chapter 16, and Chapter 17 contains a general discussion of the space of string vacua, in particular those resembling the SM or MSSM.

The optimum use of this book requires basic background of quantum field theory, group theory, and elementary notions of the SM of particle physics and general relativity. We have attempted to reduce the mathematics to a minimum, and to introduce the necessary definitions where required (including an appendix with the main geometrical and topological concepts used in the text).

We mark with an asterisk * those sections or subsections containing relevant material which may be skipped in a first reading of the book. Concerning the references, we have preferred not to insert citations in the main text and give a Bibliography for each chapter at the end of the book. These include some references to original literature, but mostly to reviews useful to the reader interested in further details. The list of references is (admittedly and necessarily) very incomplete and we apologize to many of our colleagues

whose relevant work has not been cited. Finally, we have set up a webpage to publish corrections and errata for this book:

https://sites.google.com/site/stringtheoryandparticlephysics/

Many people and institutions have contributed to make this book possible. We thank our home institutions, the Departamento de Física Teórica of the Universidad Autónoma de Madrid (UAM), and the Instituto de Física Teórica IFT-UAM/CSIC of the Consejo Superior de Investigaciones Científicas and UAM. We thank our colleagues there, for creating a supportive and stimulating environment. A.M.U. also thanks the CERN TH group, for being "home" during the first half of this project. We are grateful to our colleagues and collaborators, for all the discussions during these years. In particular, we thank Luis Aparicio, Gerardo Aldazabal, Pablo G. Cámara, David G. Cerdeño, Anamaria Font, Iñaki Garcia-Etxebarria, Fernando Marchesano, Christoffer Petersson, Fernando Quevedo, Graham Ross, and Pablo Soler, for carefully reading selected chapters and making many improving suggestions. We also thank Bert Schellekens for discussions and for providing us with edited figures from his work. We are also grateful to the Cambridge University Press team, and especially to Simon Capelin, for suggesting the project, and for the gentle management throughout the process of writing. We finally thank our families, for giving the patience and support that is always required in such a demanding enterprise.