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PARTICLE PHYSICS OF BRANE WORLDS AND EXTRA DIMENSIONS

The possibility that we live in a higher-dimensional world with spatial dimensions greater than three started with the early work of Kaluza and Klein. However, in addressing experimental constraints, early model-builders were forced to compactify these extra dimensions to very tiny scales. With the development of brane-world scenarios, it became possible to consider novel compactifications which allow the extra dimensions to be large or to provide observable effects of these dimensions at experimentally accessible energy scales.

This book provides a comprehensive account of these recent developments, keeping the high-energy physics implications in focus. After a historical survey of the idea of extra dimensions, the book deals in detail with models of large extra dimensions, warped extra dimensions and other models such as universal extra dimensions. The theoretical and phenomenological implications are discussed in a pedagogical manner for both researchers and graduate students.

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To Gita, Ira and Oindrila

Contents

Preface

The gods love what is mysterious, and dislike what is evident.
Brihadaranyaka Upanishad IV.2.2

For 49 out of the 50 centuries of recorded history, the idea of extra dimensions of space was the province of the mystic, the crank and the trickster. For what could be more obvious than the fact that there are three dimensions – length, breadth and height – as every schoolchild knows? Take a brick, for example, which is so reassuringly solid, and seems so uncompromisingly three-dimensional. Yet, for the last century or so, modern atomic science has been telling us that the solid brick is 99.99999999999% empty space. What remains is some little bits of matter, flying around eternally, and held together by electromagnetic pulls and pushes of incredible strength. This may seem bizarre and unreal, but that's how it is.

We have learnt, therefore, that 'common sense' – or rather, the evidence of our five senses – is not a trustworthy guide to the world when we try to perceive it at length scales much below the size of an average human. Once we are trained to have an open mind in his way, there is no problem at all in conceiving of more dimensions of space – they just have to be curled up into tiny loops, or spheres or higher dimensional compact objects. If the size of these is below the resolution of the human eye (or any instruments which aid the human eye), these extra dimensions will be invisible, just as atoms and molecules were at the time they were conceived of.

Most scientists encounter curled-up dimensions without realising it, when they study the quantum physics of solids. There, one can set up a wave function of an electron in a solid by invoking a 'periodic boundary condition', which is another way of saying that the co-ordinates are curled up. In fact, a three-dimensional solid is actually treated in the textbooks as a 3-torus, which is a complicated topological object that cannot be drawn on paper. If we can get useful and experimentally verifiable results by assuming a block of copper, for example, to be a 3-torus, surely it is not too much of a flight of fancy to assume that the selfsame block also has other dimensions, similarly curled-up, which are too small to be seen?

This fascinating question was raised in the early half of the twentieth century, and it continues, after a hundred years, to excite the curiosity of the researcher. During this period, extra dimensions have come (and sometimes gone) in various guises, first as a route to unification of forces, then as a support to string theories, later as a solution to the gauge-hierarchy problem and finally as an explanation of dark matter. As someone was heard to remark, extra dimensions have been used to do everything except make coffee!

The authors of this work knew, therefore, when undertaking to write a book on this subject, that it would not be an easy task. For the subject of extra dimensions, apart from having a long history, has grown today to span almost every branch of theoretical high-energy physics. Some of the developments are highly mathematical while others are purely experimental. We have, therefore, tried to create a work which reflects the flavour of our own laboured journey through this subject. Part of the development is pedagogic, and part is more like a monograph. We have deliberately chosen not to try to be comprehensive and cover everything in this area, for, apart from the problem of feasibility, this would swamp the reader with an intimidating amount of information.

This book is meant for graduate students and researchers in high-energy physics who wish to learn about extra dimensions and their impact on high-energy physics research in the last 15 years or so. After a brief warm-up, where the historical origins of extra dimensions are narrated, we introduce the early theories of Kaluza and Klein, and their immediate followers. This is followed by reviews of the Standard Model of particle physics, of string theory, and of effective theories, which form, so to say, the flesh that clothes the skeletal framework of extra dimensions. We then describe the three major paradigms developed over the last decade and a half, viz. large (flat) extra dimensions, universal (flat) extra dimensions and, finally, warped extra dimensions. In each case, we describe the theoretical model, show how to obtain the particle masses and interactions and then discuss how it may be possible to observe them, both in terrestrial experiments and in astrophysical observations, as the case may be.

Not suprisingly, this book has been a long time in the making. During this period, and before, we have been helped in various ways by so many people that it is a difficult task to remember all those whose names we need to include among our list of acknowledgements.

Primary thanks go to all our collaborators, Ben Allanach, Gautam Bhattacharyya, Biplob Bhattacherjee, Prasanta Kumar Das, Amit Chakraborty, Anindya Datta, Sukanta Datta, Dilip Kumar Ghosh, Rohini M. Godbole, Monoranjan Guchait, Ambreesh K. Gupta, Abhishek Iyer, Partha Konar, Anirban Kundu, Smaragda Lola, Uma Mahanta, Farvah Nazila Mahmoudi, Ushoshi Maitra, Namrata Manglani, Prakash Mathews, Naba K. Mondal, Biswarup Mukhopadhyaya, Ayon Patra, Poulose Poulose, Santosh Kumar Rai, V. Ravindran, Dhruv Ringe, Sophie Renner, Tousik Samui, Saswati Sarkar, Jordan P. Skitrall, W. L. van Neerven and Sudhir Vempati.

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Finally, to the prospective readers of this work we extend thanks in advance. Every time a reader gains something by reading this book, one little bit of our efforts will have been worthwhile.