Lecture Notes in Physics

The Lecture Notes in Physics

The series Lecture Notes in Physics (LNP), founded in 1969, reports new developments in physics research and teaching – quickly and informally, but with a high quality and the explicit aim to summarize and communicate current knowledge in an accessible way. Books published in this series are conceived as bridging material between advanced graduate textbooks and the forefront of research and to serve three purposes:

- to be a compact and modern up-to-date source of reference on a well-defined topic
- to serve as an accessible introduction to the field to postgraduate students and nonspecialist researchers from related areas
- to be a source of advanced teaching material for specialized seminars, courses and schools

Both monographs and multi-author volumes will be considered for publication. Edited volumes should, however, consist of a very limited number of contributions only. Proceedings will not be considered for LNP.

Volumes published in LNP are disseminated both in print and in electronic formats, the electronic archive being available at springerlink.com. The series content is indexed, abstracted and referenced by many abstracting and information services, bibliographic networks, subscription agencies, library networks, and consortia.

Proposals should be sent to a member of the Editorial Board, or directly to the managing editor at Springer:

Christian Caron
Springer Heidelberg
Physics Editorial Department I
Tiergartenstrasse 17
69121 Heidelberg / Germany
christian.caron@springer.com

M. Kuster
G. Raffelt
B. Beltrán (Eds.)

Axions

Theory, Cosmology, and Experimental Searches

Springer

Markus Kuster
TU Darmstadt
Institut für Kernphysik
Schloßgartenstr. 9
64289 Darmstadt, Germany
markus.kuster@cern.ch

Berta Beltrán
University of Alberta
11322-89 Av
Edmonton, AB, Canada
T6G 2G7
bbeltran@phys.ualberta.ca

Georg Raffelt
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)
Föhringer Ring 6
80805 München, Germany
raffelt@mppmu.mpg.de

M. Kuster et al. (Eds.), *Axions: Theory, Cosmology, and Experimental Searches*, Lect. Notes Phys. 741 (Springer, Berlin Heidelberg 2008), DOI 10.1007/ 978-3-540-73518-2

ISBN: 978-3-540-73517-5 e-ISBN: 978-3-540-73518-2

Lecture Notes in Physics ISSN: 0075-8450

Library of Congress Control Number: 2007936166

Cover design: eStudio Calamar S.L., F. Steinen-Broo, Pau/Girona, Spain

Printed on acid-free paper

9 8 7 6 5 4 3 2 1

springer.com

Emilio Zavattini, born on March 14th, 1927, in Rimini, Italy, distinguished physicist and source of many fertile ideas in our field, passed away on January 9th, 2007.

He will be remembered by all those who had the privilege of working with him, especially the younger generation researchers, for his keen insights and for his ability to critically question all ideas, including his own. This was a peculiar tract of his style which rendered him unique. While holding discussions with him, one was never afraid of expressing a scientific opinion, however trivial or unfounded, and he would always correct mistakes without causing embarrassment.

His early work in the field of strong and weak interactions, especially using muons, conducted at CERN and at other institutions worldwide, represents an outstanding achievement in physics. His deep interest in the structure of vacuum began with the spectroscopy of muonic atoms and led him to formulate the ideas at the basis of current searches for nonlinear effects in Maxwell's equations due to vacuum polarization, and for other new interactions at low energy scales.

This quest is still open and is being carried out today by a growing community of physicists. Many of the members of this community have been trained by him and all remember him fondly for all that he had been able to give.

Preface

Axion physics started in 1977 when Roberto Peccei and Helen Quinn proposed their solution to the strong CP problem by postulating a new U(1) symmetry. The strong CP problem is a "blemish" of the standard model of particle physics which is one of the most profound and successful theories in modern physics that has been verified by numerous experiments to very high accuracy. Associated with the Peccei-Quinn symmetry is a light and weakly-interacting particle that was named by Frank Wilczek based on experience from day-to-day life: *I named them after a laundry detergent, since they clean up a problem with an axial current* (Frank Wilczek, Nobel lecture 2004). So far the axion has remained elusive for over 30 years of intensive research, and none of the axion searches, based on either astrophysical observations or pure laboratory based experiments, was able to yield a positive signature for the axion or an axion-like particle.

The motivation of this book is to provide a starting point for graduate students and senior scientists in the field of axions and axion-like particles. We give a broad overview on the theoretical motivation of axions and axion-like particles, their implication for cosmology and astrophysics, their role as a well-motivated dark-matter candidate, and experimental axion searches. Most of this book is based on lectures given at the 1st Joint ILIAS-CERN-CAST axion training in Geneva at CERN in November 2005. Of course, the experiments and theoretical works are by far too numerous to be completely covered in a volume of lecture notes like this.

We are indebted to many people who have contributed directly or indirectly to finalize this book and to make the axion lecture series possible. Our special thanks go to the lecturers who have delivered stimulating written versions of their presentations and who have helped patiently during the preparation of the final text. We are grateful to our colleagues of the CAST collaboration and numerous helpers whose assistance was crucial, especially for the organization of the lecture series and for the day-to-day running of the meeting. We owe special thanks to Konstantin Zioutas for his support, who right from the conception of the first idea was convinced that the time was ripe for a lecture series on axion-related physics.

We thank the network on direct dark matter detection of the ILIAS integrating activity of the European Union (contract number: RII3-CT-2003-506222) for support and CERN for hosting the meeting.

Kingston, Darmstadt, München, February 2007

Berta Beltrán, Markus Kuster, and Georg Raffelt

Contents