LECTURE NOTES IN PHYSICS

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(Eds.)

Planck Scale Effects in Astrophysics and Cosmology

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Preface

This volume is composed of notes from lectures given at the 40th Karpacz Winter School, which focused on "Quantum Gravity Phenomenology" particularly its applications in astrophysics and cosmology.

After several decades in which the quantum-gravity problem was studied in a way that did not involve at all the confrontation with experiments [1, 2], over the last few years the idea of testing quantum-gravity ideas using experimental data has attracted significant interest. It was just around the time of the 35th Karpacz Winter School [3] that this change of attitude materialized in a part of the quantum-gravity community. And discussions that got started at the time of the 35th Karpacz Winter School finally led to the choice of topic of this 40th Karpacz Winter School.

The idea was to give students attending the school an opportunity for a short introduction to the heavily mathematical subjects that compose pure-theory quantum-gravity research, and then expose them to the core ideas that allow us to test some Planck-scale effects, especially in astrophysics and cosmology.

The lectures by Alvarez provide a brief introduction and review of string theory and loop quantum gravity, the two most popular approaches to the quantum-gravity problem. His lectures of course do not provide a detailed account of all of the technical developments in these heavily technical fields, but they strike a nice balance, combining an elementary technical introduction to the subjects with a perspective which emphasizes some key strengths and some key weaknesses of each of these two approaches. Readers interested in a more detailed technical introduction to string theory and loop quantum gravity will find useful the [4, 5] and [6, 7, 8, 9], respectively.

On the loop-quantum-gravity side the lectures by Smolin nicely complement Alvarez's lectures. In fact, Smolin provides a pedagogical introduction to some advanced aspects of the loop-quantum-gravity research program which have recently taken center stage. In particular, in Smolin's lecture notes the reader is exposed to the idea of recovering Minkowski space, in quantum gravity, only through a procedure which requires, as an intermediate step, the (quantum) description of deSitter spacetime.

Some advanced topics in "loop quantum gravity" were also introduced in the invited seminars by Pullin, which are not covered in this volume. Following the line of analysis of [10] and references therein, he presented the "consistent discretization" approach to general relativity, showing that this leads to a theory that has as its physical space what is usually considered the kinematical space of loop quantum gravity.

A first introduction to the ideas and to the most fundamental techniques used in quantum-gravity phenomenology is given in the lecture notes by Amelino-Camelia, who also stresses the importance of relying on some suitable test theories in developing this phenomenology.

The theme of working with test theories and pushing forward the experimental bounds on some commonly-adopted reference test theories was further explored in the lectures by Laemmerzahl. His lectures focus on the use of interferometry in various areas of interest for the quantum-gravity problem, including tests of the equivalence principle and tests of Lorentz symmetry.

In addition to parts of the lectures by Amelino-Camelia and Laemmerzahl, several other lectures also focused or at least touched upon the subject of the fate of Lorentz symmetry in quantum-gravity theories. The fact that in various approaches to the quantum-gravity problem there is some evidence of departures from Lorentz symmetry, and the fact that several observatories are preparing to provide us with a gigantic leap forward in the quality of Lorentz-symmetry tests, combined to bring this subject to the top of the list of priorities for the School. On the theory side a key issue here is the one of establishing whether Lorentz symmetry is "broken", in the sense commonly encountered in the analysis of particle physics in the presence of external media, or "deformed", in the sense of the "doubly-special relativity" proposal of [11, 12]. While the various scenarios for broken Lorentz symmetry were discussed briefly when appropriate in various lectures, the concept of deformation of Lorentz symmetry was introduced pedagogically in the dedicated lectures by Kowalski-Glikman, since this familiar concept of broken symmetries did not require a significant tutoring effort. His lectures emphasize in particular some delicate issues that have emerged in doubly-special-relativity research, including the role that, at least to some extent, could be played by the mathematics of κ-Poincaré Hopf algebras.

From a more phenomenological perspective the possibility of Planck-scale modifications of Lorentz symmetry was the main focus of the lectures by Jacobson, Grillo and Piran. The lectures delivered by Jacobson gave an overview of several opportunities that modern astrophysics provides for testing Lorentz symmetry with Planck-scale sensitivity. Grillo focused on the study of the cosmic-ray spectrum, especially as it will soon be studied by the Pierre Auger Observatory, which should be the best opportunity for dramatic improvement in the quality of our tests of Planck-scale modifications of Lorentz symmetry. Piran gave detailed pedagogical lectures on the research line that intends to constrain Planck-scale departures of Lorentz symmetry using data on gamma-ray bursters, and in particular he stressed some features of gamma-ray bursters which could effectively could the act as troublesome background for the quantum-gravity studies.

The lectures by Mavromatos and Ng focused on some examples of phenomenological programs which can be primarily motivated by some descriptions of "spacetime foam". Both lectures provided further encouragement for the idea of Planck-scale departures from Lorentz symmetry. Mavromatos emphasized even more strongly the possibility of Planck-scale departures from CPT symmetry, and discussed a rich CPT phenomenology. Ng also discussed some other spacetime-foam effects which could be investigated with modern interferometers.

Martin's lectures gave a pedagogical introduction to the research area that investigates the possibility of quantum-gravity effects in cosmology.

This "quantum-gravity cosmology" was also the subject of invited seminars by de Bernardis, which are not covered in this volume. He gave a detailed description of the BOOMERANG and WMAP experiments following roughly the line of analysis presented in [13].

The invited seminars by Lipari, which were based on some of his works in preparation, provided a perspective on several aspects of gamma-ray and cosmic-ray physics, which are relevant for the topics covered by other lecturers.

The invited seminar by Urrutia presented yet another intriguing perspective on the phenomenology of Planck-scale departures from Lorentz symmetry, following roughly the line of analysis presented in [14].

Also the seminars contributed by several participants were very important for the overall balance of the school. In particular, lively discussions were generated by the seminars by Arzano [15], Bruno [16], Doplicher [17], Hinterleitner [18], Liberati [19], Mandanici [20], Martinetti, Mattingly [19], Mendez [21], Oriti, Penna-Firme, Rembielinski, Rychkov [22], Sudarsky [23] and Turko.

We owe special thanks to all lecturers and all other speakers, and we are particularly grateful for the lucky assortment of students and senior participants who attended the school. The enthusiasm of the students for all lectures was a major source of energy for the school. We were amazed to see students requesting on several occasions additional hours of lecture by some lecturers, which were often scheduled after dinner (the feared "8pm–10pm extra lectures"). Perhaps the unfriendly weather outside the hotel that hosted the school had something to do with all this enthusiasm for lectures, but it nonetheless contributed to a wonderful 10 days of physics.

Finally we would like to thank the Rector of the University of Wroclaw, the Polish Ministry of Education, the Foundation for Karpacz Winter Schools in Theoretical Physics, and the European Physical Society for their generous financial support. Thanks are due Professor Jerzy Lukierski, Director of the Institute for Theoretical Physics of the University of Wroclaw, for his encouragement support and help, to Mrs. Katarzyna Imilkowska, who did a great job

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Giovanni Amelino-Camelia
April, 2005 *Jerzy Kowalski-Glikman*

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Contents

Planck Scale Kinematics and the Pierre Auger Observatory

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Abstract. Quite unexpectedly, to many of us at least, Planck scale physics has in last years made irruption in present experimental physics. In these lectures I try to describe why this happened particularly in relation to Ultra High Energy Cosmic Ray Physics, and will discuss the potentialities of experiments in this field, in particular of the Pierre Auger Observatory. I will also present some (more theoretical) speculations.

1 Motivations

In this report I will mix theoretical and phenomenological considerations. However, being a theorist who has spent a large part of his activity as a Cosmic Ray experimentalist, I will always try to keep experimental verification/falsification as the main guide in approaching theories, and more so in this field connected to the possibly most complex entities (Quantum Gravity effects) for the experimentalist (and even for most theorists). In this connection I think that a description of how I entered in this field might be of some interest.

In fact I remember exactly how this happened: I was attending a seminar from a colleague of mine (experimentalist, we were both part of the MACRO experiment at Gran Sasso Laboratory) reporting about the so called Greisen-Zatsepin-Kuzmin break [1] and the first experimental data from AGASA [2] which did not show it. While I was mentally searching for possible explanations, I realized that the processes giving rise to the expected break are in fact *low energy* processes, since it is always possible to boost back the UHE proton to a frame where it is at rest, and there the photon must have an energy only larger than $\approx$100 MeV to photoproduce a pion. So, no particle physics explanation for its possible absence was at hand.

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On the other hand I appreciated that in fact the expected presence of the break is entirely based on an extrapolation of the validity of the Lorentz transformations up to Lorentz factors $\gamma_L \approx 10^{11}$ or velocities $1 - \beta \approx 10^{-22}$. A verification of the presence of the break would imply a *direct* comparison of physics in two frames moving at extreme relative speed.

Unfortunately (and contrary to what is often said in the literature) the absence of the break *does not* point by itself to a violation of Lorentz invariance: since we ultimately do not know the origin of the highest energy particles in the Cosmic Radiation, there are at least an handful of more mundane explanations for its absence. I will discuss later under which conditions Cosmic Ray experiments would imply such a radical departure, but from what I said it is clear that this is tied to the recognition of the sources of these particles.

In March 1997 I presented under the title "The Auger Observatory as a test ground for very fundamental physics" a short report at the European Auger meeting that was held in Gran Sasso, and (in collaboration with P. Blasi) we sent an abstract to the 1997 ICRC conference. However, since we were not able at the moment to make a more quantitative description of possible departures from Lorentz Invariance, we withdraw the paper.

Seven years have passed, and I have discovered a very interesting theoretical physics that was largely unknown to me. We also discovered that some related (and prophetic) ideas were presented in a paper by D.A. Kirzhnits and V.A. Chechin in 1971, shortly after the prediction of the GZK break [3] .

What has really dramatically changed in the last few years has been the recognition that the effects of Planck scale physics need not to be confined to the Planck regime. There are several ways to understand why this happens at an intuitive level. First, violations of Lorentz invariance should be parameterized by some indicator of "relativisticity" so to say; for instance at an energy of 10^{20} eV a proton, on a logarithmic scale is nearer to the Planck scale (10^{28} eV) than to its rest mass.

Second, in the Cosmic Microwave Background Radiation (CMBR) frame, i.e. the frame in which the CMBR is isotropic with a photon energy distribution corresponding to a Planckian of temperature $\approx 2.7°$K, a 10^{20} eV proton only needs a fractional gain in energy $\approx 10^{-22}$ to perform the transition to the final πp state. Of course there is nothing miraculous in this since Lorentz invariance guarantees that this is exactly equivalent to what happens in a frame in which the proton is at rest and the photon has an energy larger than $\approx$100 MeV. But this also displays the fact that even very tiny violations of relativistic invariance are bound to give, in some selected reactions at least, observable effects.

And, third, an example of reactions very sensitive to even small departures from L.I. is given by particle production thresholds, which typically sensitively depend on the *rest masses* of the (massive) involved particles. The simplest way of parameterizing departures from relativistic invariance is to change the form of the LI dispersion relation $E^2 - p^2 = m^2$ by rewriting it as $E^2 - p^2 = \mu^2(E,p)$. This may be seen as the introduction of an (energy and momentum dependent) effective mass that in turn will affect the threshold energy-momenta, in principle differently in different reference frames.

2 Introduction

The hunt for possible minuscule violations of the fundamental Lorentz invariance (LI) has been object of renewed interest, in particular because it has been understood that cosmic ray physics has an unprecedented potential for investigation in this field [3, 4, 5, 6, 7, 8]. Some authors [5, 6, 9] have even invoked possible violations of LI as a plausible explanation to some puzzling observations related to the detection of ultra high energy cosmic rays (UHECRs) with energy above the so-called GZK feature [1], and to the unexpected shape of the spectrum of photons with super-TeV energy from sources at cosmological distances.

Both types of observations have in fact many uncertainties, that will be diffusely discussed in the following, either coming from limited statistics of very rare events, or from accuracy issues in the energy determination of the detected particles, and it is very possible that the solution to the alleged puzzles will come from more accurate observations rather than by a violation of fundamental symmetries.

For this reason, from the very beginning we proposed [7] that cosmic ray observations should be used as an ideal tool to constrain the minuscule violations of LI, rather than as evidence for the need to violate LI. The reason why the cases of UHECRs and TeV gamma rays represent such good test sites for LI is that both are related to physical processes with a kinematical energy threshold, which is in turn very sensitive to the smallest violations of LI. UHECRs are expected to suffer severe energy losses due to photopion production off the photons of the cosmic microwave background (CMB), and this should suppress the flux of particles at the Earth at energies above $\sim 10^{20}$ eV, the so called GZK feature.

Present largest operating (or just ended) experiments are AGASA [10] and HiRes [11], and they do not provide strong evidence either in favor or against the detection of the GZK feature [12]. A substantial increase in the statistics of events, as expected with the Auger project [13] and with EUSO [14], should dramatically change the situation and allow to detect the presence or lack of the GZK feature in the spectrum of UHECRs (see next section for more detail). Moreover they should in principle be able to perform rather sensitive anisotropy studies, in particular to search for possible correlations with distant sources.

These are the observations that will provide the right ground for imposing a strong limit on violations of LI.In this report I will direct myself only to Ultra High Energy hadronic Cosmic rays. It is perhaps worth remembering that a potentially very interesting arena for detecting violations of LI is also the study of TeV γ sources. For the case of TeV sources, the process involved is pair production [15] of high energy gamma rays on the photons of the infrared background. Also in this case, a small violation of LI can move the threshold to energies which are smaller than the classical ones, or move them to infinity, making the reactions impossible. The detection of the GZK suppression or the cutoff in the gamma ray spectra of gamma ray sources at cosmological distances will prove that LI is preserved to correspondingly high accuracy [7].

The recipes for the violations of LI generally consist of requiring an *explicit* modification of the dispersion relation of high energy particles, due to their propagation in the "vacuum", now affected by quantum gravity (QG). This effect is generally parameterized by introducing a typical mass, expected to be of the order of the Planck mass (M_P), that sets the scale for QG to become effective.

This approach has been extensively discussed in the literature (and in several reports in these proceedings) so it will be presented here for completeness, and to set the ground for comparison with possible experimental outcomes of the new experiments, in particular of the Pierre Auger Observatory.

In particular we discuss at some length the possible outcomes of the next experiments, and their relevance for the detection of (Quantum Gravity inspired) modifications of special relativity.

We next pass to a more speculative level. Explicit modifications of the dispersion relation are not really necessary in order to produce detectable effects, as was recently pointed out in [16, 17, 18, 19] for the case of propagation of UHECRs. It is in fact generally believed that coordinate measurements cannot be performed with precision better than the Planck distance (time) $\delta x \geq l_P$, namely the distance where the metric of space-time must feature quantum fluctuations.

A similar line of thought implies that an uncertainty in the measurement of energy and momentum of particles can be expected, according with the relation $\delta p \simeq \delta E \simeq p^2/M_P$. As discussed also in [17, 18] the apparent problem of super-GZK particles might find a solution also in the context of this uncertainty approach.

In the second part of these lectures we discuss this approach in some detail, by taking into account the effects of the propagation of CRs in the QG vacuum in the presence of the universal microwave background radiation. A fluctuating metric implies that different measurements of the particle energy or momentum may result in different outcomes.

A consequence of this approach is that particles with classical energy below the standard Lorentz invariant threshold have a certain probability of interacting. In the same way, particles above the classical threshold have a finite probability of evading interaction. We show here that the most striking consequences of the approach described above derive from low energy particles rather than from particles otherwise above the threshold for photopion production.

However, the possibility of a fluctuating energy and momentum is mainly constrained by other processes that could arise. The fluctuations of energy