Particle Physics

A Los Alamos Primer

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Los Alamos National Laboratory

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Preface

On the cover a mandala of the laws of physics floats in the cosmos of reality. It symbolizes the interplay between the inner world of abstract creation and the outer realms of measurable truth. The tension between these two is the magic and the challenge of fundamental physics.

According to Jung, the "squaring of the circle" (the mandala) is the archetype of wholeness, the totality of the self. Such images are sometimes created spontaneously by individuals attempting to integrate what seem to be irreconcilable differences within themselves. Here the mandala displays the modern attempt by particle physicists to bring together the basic forces of nature in one theoretical framework.

The content of this so-called standard model is summarized by the mysterious-looking symbols labeling each force: U(1) for electromagnetism, SU(2) for weak interactions, $SU(3)_C$ for strong interactions, and SL(2C) for gravity; each symbol stands for an invariance, or symmetry, of nature. Symmetries tell us what remains constant through the changing universe. They are what give order to the world. There are many in nature, but those listed on the mandala are special. Each is a *local* symmetry, that is, it manifests independently at every space-time point and therefore implies the existence of a separate force. In other words, local symmetries determine all the forces of nature. This discovery is the culmination of physics over the last century. It is a simple idea, and it turns out to describe *all* phenomena so far observed.

Where does particle physics go from here? The major direction of present research (and a major theme of this issue) is represented by the spiral that starts at electromagnetism and turns into the center at gravity. It suggests that the separate symmetries may be encompassed in one larger symmetry that governs the entire universe—one symmetry, one principle, one theory. The spiral also suggests that including gravity in such a theory involves understanding the structure of space-time at unimaginably small distance scales.

Julian Schwinger, whose seminal idea led to the modern unification of electromagnetic and weak interactions, regards the present emphasis on unification with skepticism: "It's nothing more than another symptom of the urge that afflicts every generation of physicists—the itch to have all the fundamental questions answered in their own lifetime."* To others the goal seems tantalizingly close, an achievement that may be reached, if not this year—then maybe the next . . . .

The hope of unification depends on a second theme of this issue, symbolized by the ants and elephants walking round the mandala. These creatures are our symbol of scaling, the sizing up and sizing down of physical systems. Strength (or any other quality, for that matter) may look different on different scales. But if we look hard enough, we can find certain invariances to changes in scale that define the correct variables for describing a problem. Why do ants appear stronger than elephants? Why does the strong force look weak at high energies? How could all the forces of nature be manifestations of a single theory? These are the questions explored in "Scale and Dimension—from animals to quarks," a seductively playful article that leads us to one of the most important contributions to modern physics, the renormalization group equations of quantum field theory. The insights about scaling gained from these equations are important not only to elementary particle physics but also to phase transition theory and the dynamics of complex systems.

All the articles in this issue were written by scientists who care to tell not only about their own research but about the whole field of particle physics, its stunning achievements and its probing questions. Outsiders to this field hear the names of the latest new particles, the buzz words such as grand unification or supersymmetry, and the plans for the United States to regain its leadership in this glamorous, high tech area of big science. But what is the real progress? Why does this field continue to attract the best minds in science? Why is it a major achievement of human thought? From a distance it may be hard to tell—except that it satisfies some deep urge to understand how the world works. But if one could be given a closer look at the technical content of this field, its depth and richness would become apparent. That is the aim of the present issue.

The hardest job was defining the technical level. How could the framework of the standard model be appreciated by someone unfamiliar with symmetry principles? How could modern particle physics research, all of which builds on the standard model, be understood by someone unfamiliar with what everyone in the field takes for granted? We hope we have solved this problem by presenting some of the major concepts on several levels and in several different places. We even include our own reference material, a remarkably clear and friendly set of lecture notes prepared especially for this issue.

As one who was trained in this field, I returned to it with some trepidation—to deal with the subject matter, which had been so difficult, and with the personalitites competing in the field, who sometimes ride roughshod over each other as they battle these unruly abstractions. Much to my delight and the delight of the *Los Alamos Science* staff, the experience of preparing this issue was immensely enjoyable and rewarding. The authors were enthusiastic about explaining and re-explaining, about considering the essence of each point one more time to make sure that the readers too would be able to grasp it. Their generosity and interest made it fun for us to learn. May this presentation also be a treat for you.

Necia Grant Cooper
1984

This quote appeared in "How the Universe Works" by Robert P. Crease and Charles C. Mann (**The Atlantic Monthly, ***August, 1984), a fast-paced article about the history of the electoweak theory.

Introduction

Beginning with the dramatic discovery of the J/ψ particle in 1974, particle physics has gone through a remarkably productive and exciting period. Quantum field theory, developed during the 1940s and '50s but abandoned in the '60s, was re-established as the language for formulating theoretical concepts. The unification of the weak and electromagnetic interactions via a so-called non-Abelian gauge theory could only be understood in this framework. A similar theory of the strong interactions, quantum chromodynamics, was also constructed during this period, and nowadays one refers to the total package of the strong and electroweak theories as "the standard model." Over the last decade the predictions of the standard model have been spectacularly confirmed, so much so that it is now almost taken for granted as embodying all physics below about 100 GeV. The culmination of this exuberant period was the inevitable discovery in 1983 of the $W^{\pm}$ and Z^0 particles, the massive bosons predicted by the standard model to mediate the weak interactions. Although the masses of these particles were precisely those predicted by the SU(2) × U(1) electroweak theory, their discovery was almost anticlimactic, so accepting had the particle-physics community become of the standard model. Indeed, future research in particle physics is often referred to as "physics beyond the standard model," an implicit tribute to the progress of the past decade.

The development of the standard model during the 1970s brought with it a lexicon of new words and concepts—quark, gluon, charm, color, spontaneous symmetry breaking, and asymptotic freedom, to name a few. Supersymmetry, preons, strings, and worlds of ten dimensions are among the buzz words added in the '80s. While scientists, engineers, and even many lay people will recognize some subset of these words, only a few have more than a superficial understanding of the profound achievement they denote. Add to this the demand by particle physicists for several billion dollars to build a super-accelerator in order to explore "physics beyond the standard model," and one can sense the gap between the particle physicist and his "public" reaching irreparable proportions. On the other hand there remains an endless wonder and fascination in the public's eye for such speculative conceptual ideas, which are more usually associated with the literature of science fiction than with *Physical Review*.

It was with some of these thoughts in mind that a group of us at Los Alamos National Laboratory decided to put together a series of pedagogical articles explaining in relatively elementary scientific language the accomplishments, successes, and projected future of high-energy physics. The articles, intended for a wide scientific audience, originally appeared in a 1984 issue of *Los Alamos Science*, a technical publication of the Laboratory. Since that time they have been used as a teaching tool in particle-physics courses and as a reference source by experimentalists in the field.

Particle Physics—A Los Alamos Primer is basically an updated version of the original *Los Alamos Science* issue. We believe it will continue to help educate undergraduate and graduate students as well as bridge the gap between experimentalists and theorists. We are also confident that it will help non-experts to develop a good feel for the subject.

The text consists of eight "chapters," the first five devoted to the concepual framework of modern particle physics and the last three to experiments and accelerators. Each is written by a separate author, or group of authors, and is to a large extent self-contained. In addition, we have included a round table among several particle physicists that addresses some of the broader issues facing the field. This discussion is in some ways a unique evaluation of the present status of particle physics. It is quite personal and idiosyncratic, sometimes irreverent, and occasionally controversial. For the non-expert it is probably the place to begin!

The first article addresses the question of scaling. In its broadest sense this lies at the heart of any attempt to unify into one theory the fundamental forces of Nature—forces seemingly so very different in strength. "Scale and Dimension—From Animals to Quarks" begins by reviewing in an elementary and somewhat whimsical fashion the whole question of scale in classical physics and then introduces the more sophisticated concept of the renormalization group. The renormalization group is really no more than a generalization of classical dimensional analysis to the area of quantum field theory: it answers the seminal question of how a physical system responds to a change in scale. The concept plays a central role in the modern view of quantum field theory and has been particularly successful in elucidating the nature of phase transitions. Indeed, it is from this vantage point that the intimate relationship between particle and condensed-matter physics has developed. Clearly, the manner in which physics evolves from one energy or length scale to another is of fundamental importance.

The second article, "Particle Physics and the Standard Model," addresses the question of unification with an elementary yet comprehensive discussion of how the famous electroweak theory is constructed and works. The role of internal symmetries and their incorporation into a principle of local gauge invariance and subsequent manifestation as a non-Abelian gauge field theory are explained in a pedagogical fashion. The other component of the standard model, namely quantum chromodynamics (QCD), the theory of the strong interactions, is similarly treated in this article. Again, the discussion is rather elementary, beginning with an exposition of the "old" SU(3) of the "Eightfold Way" and finishing with the field theory of quarks and gluons. For the more ambitious reader we have included a set of "lectures" by Richard Slansky that give some of the technical details necessary in going "from simple field theories to the standard model." Crucial concepts such as local gauge invariance, spontaneous symmetry breaking, and emergence of the Higgs particles that give rise to the masses of elementary particles are expressed in the mathematical language of field theory and should be readily accessible to the serious student of the field. These lectures are very clear and provide the reader with the explicit equations embodying the physics discussed in the article on the standard model.

Following this review of accepted lore, we begin our journey into "physics beyond the standard model" with an essay on supergravity by Slansky entitled "Toward a Unified Theory." In it he discusses some of the speculative ideas that gained popularity in the late 1970s. Among them are supersymmetry (a proposed symmetry between fermions and bosons) and the embedding of our four-dimensional space-time world in a larger number of dimensions. Supergravity, a theory that encompasses both of these ideas, was the first serious attempt to include Einstein's gravity in the unification scheme. This article also includes a description of superstring theory, which has gained tremendous popularity just in the last year or so. Slansky explains how the shortcomings of the supergravity scenario are circumvented by basing a unified theory on elementary fibers, or strings, rather than on point particles. This area of research is in a state of flux at the moment, and it is still far from clear whether strings really will form the basis of the "final" theory. The problems are both conceptual and technical. Conceptually there is still no hint as to what principles are to replace the equivalence principle and general coordinate invariance, which form the bases of Einstein's gravity. Technically, the mathematics of string theory is beyond the usual expertise of the theoretical physicist; indeed it is on the forefront of mathematical research itself. This may be the first time for a hundred years or more that research in physics and mathematics has coincided. Some may view this as a bad omen, others as the dawning of a new exciting age leading to the equations of the universe! Only time will tell.

A less ambitious use of supersymmetry has been in the attempts to unify, without gravity, the electroweak and strong theories of the standard model. Stuart Raby, in his article "Supersymmetry at 100 GeV," discusses some of these efforts by concentrating on the phenomenological implications of a world in which every boson has a fermion partner and vice versa. These include a possible explanation for why proton decay, certainly one of the more dramatic predictions of grand unified theories, has not yet been seen. Supersymmetric phenomenology has served as an important guide for speculating about what can be seen at new accelerators. A special feature of this article is the self-contained section "Supersymmetry in Quantum Mechanics," in which Raby explains this novel space-time symmetry in a setting stripped of all field-theoretic baggage.

One of the more mysterious problems in particle physics is "the family problem" described in an article of that title by Terry Goldman and Michael Nieto. The apparent replication of the electron and its neutrino in at least two more families differing only in their mass scales has remained a mystery ever since the discovery of the muon. This replication, exhibited also by the quarks, can be accommodated in unified theories, though no satisfactory explanation of the family structure, nor even a prediction of the total number of families, has been advanced. The phenomenology of this problem as well as some attempts to understand it are carefully reviewed. An addendum to the original article presents a slightly more technical discussion of how experiments involving the third quark family might extend our knowledge of CP violation. This symmetry violation remains perhaps the most mysterious aspect of the known particle phenomenology.

The next three articles concern the experimental side of particle physics. Although the choice of Los Alamos experiments to illustrate certain points does reflect some parochial interests of the authors, these articles succeed in providing a broad overview of experimental methodology. In this era of elaborate detection techniques requiring extensive collaboration, it is often difficult for the uninitiated to unravel the complicated machinations that are involved in the experimental process. In "Experiments to Test Unification Schemes" Gary Sanders presents a very clear exposition of the physics input to this process. Indeed, as if to emphasize the departure from the world of theory, he has included a brief page-and-a-half précis subtitled "An Experimentalist's View of the Standard Model." For the beginner this might be read immediately following the round table! Sanders describes in some detail four experiments designed specifically to test the standard model, all being conducted at Los Alamos. Each is a "high-precision" experiment in which, say, a specific decay rate is measured and compared with the value predicted by the standard model. These experiments are prototypical of the kind that have been and will continue to be done at accelerators around the world to push the theory to its limits. Most exciting, or course, would be the observation of some deviation from the standard model that could be associated with grand unification. However, in an addendum Sanders reports that no such deviations were seen in the data from the Los Alamos experiments and others. So far the standard model has stood the test of time.

The following article by Peter Rosen, "The March toward Higher Energies," surveys the high-energy accelerator landscape beginning with a historical perspective and finishing with a glimpse into what we might expect in the not-too-distant future. The emphasis here is on tests of the standard model and searches for new and exotic particles not included in it. The traditional methodology is quite simple: go for the highest energy possible. This has certainly been successful in the past, and we have no reason to believe that it won't be successful in the future. Thus, there is a push to build a giant superconducting supercollider (SSC) that could probe mass scales in excess of 20 TeV, or 2×10^{13} eV. We have also included a brief report by Mahlon Wilson, an accelerator physicist, on some of the problems peculiar to the gigantic scale of the SSC.

An alternative technique for probing high mass scales is to perform very accurate experiments in search of deviations from expected results, such as those described in Sanders' article. Obviously, high-intensity beams are the desired tool in this approach. A high-intensity machine has been proposed for Los Alamos, and another brief report by Henry Thiessen, also an accelerator physicist, describes that machine and some of the questions it might answer. The reports on the SSC and LAMPF II provide an idea of what is involved in designing tomorrow's accelerators.

The final article is a review by Mike Simmons on "science underground." In it he discusses what particle physics can be learned from experiments performed deep underground to isolate rare events of interest. The most famous of these is the search for proton decay. Other experiments measure the flux of neutrinos from the sun and search for exotic particles (such as magnetic monopoles) in cosmic rays. These essential fishing expeditions use "beams" from the biggest accelerator of them all, namely the universe!

Particle Physics—A Los Alamos Primer thus provides the reader with a comprehensive, up-to-date introduction to the field of particle physics. Our belief is that it will be a useful educational guide to both the student and professional worker in the field as well as provide the general scientist with an insight into some of the recent accomplishments in understanding the fundamental structure of the universe.

In conclusion we would like to thank the staff of *Los Alamos Science* for their invaluable help in making this primer lively and accessible to a wide audience.

Geoffrey B. West
1986