QUANTUM UNIVERSE

The Revolution in 21st-Century Particle Physics

Executive Summary

What is the nature of the universe and what is it made of?
What are matter, energy, space and time?
How did we get here and where are we going?

Throughout human history, scientific theories and experiments of increasing power and sophistication have addressed these basic questions about the universe. The resulting knowledge has led to revolutionary insights into the nature of the world around us.

In the last 30 years, physicists have achieved a profound understanding of the fundamental particles and the physical laws that govern matter, energy, space and time. Researchers have subjected this "Standard Model" to countless experimental tests; and, again and again, its predictions have held true. The series of experimental and theoretical breakthroughs that combined to produce the Standard Model can truly be celebrated as one of the great scientific triumphs of the 20th century.

Now, in a development that some have compared to Copernicus's recognition that the earth is not the center of the solar system, startling new data have revealed that only five percent of the universe is made of normal, visible matter described by the Standard Model. Ninety-five percent of the universe consists of dark matter and dark energy whose fundamental nature is a mystery. The Standard Model's orderly and elegant view of the universe must be incorporated into a deeper theory that can explain the new phenomena. The result will be a revolution in particle physics as dramatic as any that have come before.

Questions for the Universe

A worldwide program of particle physics investigation is underway to explore the mysterious new scientific landscape. Nine interrelated questions define the path ahead.

Einstein's Dream of Unified Forces

1. Are there undiscovered principles of nature: new symmetries, new physical laws?
The quantum ideas that so successfully describe familiar matter fail when applied to cosmic physics. Solving the problem requires the appearance of new forces and new particles signaling the discovery of new symmetries—undiscovered principles of nature's behavior.

2. How can we solve the mystery of dark energy?
The dark energy that permeates empty space and accelerates the expansion of the universe must have a quantum explanation. Dark energy might be related to the Higgs field, a force that fills space and gives particles mass.

3. Are there extra dimensions of space?
String theory predicts seven undiscovered dimensions of space that give rise to much of the apparent complexity of particle physics. The discovery of extra dimensions would be an epochal

event in human history; it would change our understanding of the birth and evolution of the universe. String theory could reshape our concept of gravity.

4. Do all the forces become one?
At the most fundamental level all forces and particles in the universe may be related, and all the forces might be manifestations of a single grand unified force, realizing Einstein's dream.

The Particle World

5. Why are there so many kinds of particles?
Why do three families of particles exist, and why do their masses differ so dramatically? Patterns and variations in the families of elementary particles suggest undiscovered underlying principles that tie together the quarks and leptons of the Standard Model.

6. What is dark matter? How can we make it in the laboratory?
Most of the matter in the universe is unknown dark matter, probably heavy particles produced in the big bang. While most of these particles annihilated into pure energy, some remained. These remaining particles should have a small enough mass to be produced and studied at accelerators.

7. What are neutrinos telling us?
Of all the known particles, neutrinos are the most mysterious. They played an essential role in the evolution of the universe, and their tiny nonzero mass may signal new physics at very high energies.

The Birth of the Universe

8. How did the universe come to be?
According to cosmic theory, the universe began with a singular explosion followed by a burst of inflationary expansion. Following inflation, the universe cooled, passing through a series of phase transitions and allowing the formation of stars, galaxies and life on earth. Understanding inflation requires breakthroughs in quantum physics and quantum gravity.

9. What happened to the antimatter?
The big bang almost certainly produced equal amounts of matter and antimatter, yet the universe seems to contain no antimatter. How did the asymmetry arise?

Opportunities for Discovery

We live in an age when the exploration of great questions is leading toward a revolutionary new understanding of the universe.

"Opportunities have emerged for discovery about the fundamental nature of the universe that we never expected," Presidential Science Advisor John Marburger said recently. "Technology places these discoveries within our reach, but we need to focus efforts across widely separated disciplines to realize the new opportunities."

This report is a response to that challenge. It serves as a guide to where the search for understanding has taken us so far, and to where it is going. The chapters that follow articulate how existing and planned particle physics experiments at accelerators and underground laboratories, together with space probes and ground-based telescopes, bring within reach new opportunities for discovery about the fundamental nature of the universe.

I. Introduction

What is the nature of the universe and what is it made of?
What are matter, energy, space and time?
How did we get here and where are we going?

The quest to answer the most basic questions about the universe has reached a singular moment. As the 21st century begins, physicists have developed a commanding knowledge of the particles and forces that characterize the ordinary matter around us. At the same time, astrophysical and cosmological space observations have revealed that this picture of the universe is incomplete—that 95 percent of the cosmos is not made of ordinary matter, but of a mysterious something else: dark matter and dark energy. We have learned that in fact we do not know what most of the universe is made of.

Understanding this unknown "new" universe requires the discovery of the particle physics that determines its fundamental nature. Powerful tools exist to bring the physics within reach. With astrophysical observations, we can explore the parameters of the universe; with accelerator experiments we can search for their quantum explanation. Energies at particle accelerators now approach the conditions in the first instants after the big bang, giving us the means to discover what dark matter and dark energy are—and creating a revolution in our understanding of particle physics and the universe.

To answer the fundamental questions about the nature of the universe, astrophysical observations of the relics of the big bang must agree with data from physics experiments recreating the particles and forces of the early universe. The two ends of the exploration must meet. We will answer these challenging questions by combining what we learn from the most powerful and insightful observations and experiments in each of these approaches.

The following chapters take up in successively greater depth nine key questions that define the field. Chapter II elucidates the meaning of the questions and their implications for 21st century particle physics; Chapter III defines the scientific program to address and answer them. The tables in Chapter V summarize the U.S. facilities whose primary physics programs respond most directly to the questions.

II: The Fundamental Nature of Matter and Energy, Space and Time

Current and future particle physics experiments around the world give us the capability to address a well-defined set of questions about the basic physical laws that govern the universe. These questions, at the same time eminently familiar and profoundly revolutionary, define the path for particle physics in the 21st century.

Einstein's Dream of Unified Forces

Since Einstein, physicists have sought a unified theory to explain all the fundamental forces and particles in the universe. The result is a stunningly successful theory that reduces the complexity of microscopic physics to a set of concise laws. But these same quantum ideas fail when applied to cosmic physics. Some fundamental piece is missing; gravity, dark matter and dark energy must have quantum explanations. A new theoretical vision is required, one that embraces the Standard Model and general relativity, while resolving the mystery of dark energy. Particle accelerators provide the means to reach a unified theoretical perspective in experiments characterized by four well-defined intellectual thrusts.

1. Are there undiscovered principles of nature: new symmetries, new physical laws?

Our quest to discover the fundamental laws of nature has led to the revelation that the laws of physics, and the particles they govern, exist because of underlying symmetries of nature, some of them lost since the big bang. One such lost symmetry might be supersymmetry. Just as for every particle there exists an antiparticle, supersymmetry predicts that for every known particle there also exists a superpartner particle. Part of the strong theoretical appeal of supersymmetry, an essential part of string theory, is its possible connection to dark energy and the fact that it provides a natural candidate for dark matter, the neutralino.

The discovery of supersymmetry is an immediate experimental challenge of particle physics, followed by the exploration of its structure and the properties of the superpartner particles. Particle accelerator experiments will uncover the role of supersymmetry in a unified theory and reveal whether the neutralino superpartner accounts for dark matter.

2. How can we solve the mystery of dark energy?

Recent measurements with telescopes and space probes have shown that a mysterious force—a dark energy—fills the vacuum of empty space, accelerating the universe's expansion. We don't know what dark energy is, or why it exists. On the other hand, particle theory tells us that, at the microscopic level, even a perfect vacuum bubbles with quantum particles that are a natural source of dark energy. But a naïve calculation of the dark energy generated from the vacuum yields a value 10^{120} times larger than the amount we observe. Some unknown physical process is required to eliminate most, but not all, of the vacuum energy, leaving enough left to drive the accelerating expansion of the universe. A new theory of particle physics is required to explain this physical process.

Particle physics data point to another mysterious component of empty space, the Higgs field, that gives particles the property of mass. Without the Higgs field, electrons would fly at the speed of light, and atoms would instantly disintegrate. Are dark energy and the Higgs field related? The discovery of supersymmetry would provide crucial evidence of a possible connection. Supersymmetry provides both a natural context for the Higgs field and a possible explanation for the small but finite value of dark energy.

3. Are there extra dimensions of space?

The revolutionary concept of string theory is a bold realization of Einstein's dream of an ultimate explanation for everything from the tiniest quanta of particle physics to the cosmos itself. String theory unifies physics by producing all known forces and particles as different vibrations of a single substance called superstrings. String theory brings quantum consistency to physics with an elegant mathematical construct that appears to be unique.

Do superstrings exist? The strings themselves are probably too tiny to observe directly, but string theory makes a number of testable predictions. It implies supersymmetry and predicts seven undiscovered dimensions of space, dimensions that would give rise to much of the mysterious complexity of particle physics. Testing the validity of string theory requires searching for the extra dimensions and exploring their properties. How many are there? What are their shapes and sizes? How and why are they hidden? And what are the new particles associated with the extra dimensions?

4. Do all the forces become one?

At the most fundamental level, particles and forces may converge, either through hidden principles like grand unification, or through radical physics like superstrings. We already know that remarkably similar mathematical laws and principles describe all the known forces except gravity. Perhaps all forces are different manifestations of a single grand unified force, a force that would relate quarks to leptons and predict new ways of converting one kind of particle into another. Such a force might eventually make protons decay, rendering ordinary matter unstable.

The Particle World

Physicists have identified 57 distinct species of elementary particles and have determined many of their properties in exquisite detail. What are their roles? How will we know when we have found them all? Perhaps these particles are just different notes on a single superstring. Perhaps they are related by grand unification, or other hidden symmetries, in ways that we have yet to decipher. Unification may provide the key, the simple principle that gives particles their complex identities.

5. Why are there so many kinds of particles?

We have discovered three families of quarks and leptons, families of fundamental particles that differ only in their masses, which range from less than a millionth of the mass of an electron to the mass of an atom of gold. Just as quantum mechanics led to an understanding of the organization of the periodic table, we look to new theories to explain the patterns of elementary particles. Why do three families of particles exist, and why do their masses differ so dramatically?

Current investigations focus on developing a detailed picture of the existing patterns in the particle world. Remarkable progress has been made, especially in characterizing the quarks. But why are the patterns for leptons and quarks completely different? Detailed studies of quarks and leptons at accelerator experiments will provide the clearest insight into these issues.

6. What is dark matter? How can we make it in the laboratory?

Most of the matter in the universe is dark. Without dark matter, galaxies and stars would not have formed and life would not exist. It holds the universe together. What is it?

Although the existence of dark matter was suggested in the 1930s, only in the last 10 to 15 years have scientists made substantial progress in understanding its properties, mostly by establishing what it is not.

Recent observations of the effect of dark matter on the structure of the universe have shown that it is unlike any form of matter that we have discovered or measured in the laboratory. At the same time, new theories have emerged that may tell us what dark matter actually is. The theory of supersymmetry predicts new families of particles interacting very weakly with ordinary matter. The lightest supersymmetric particle could well be the elusive dark matter particle. We need to study dark matter directly by detecting relic dark matter particles in an underground detector and by creating dark matter particles at accelerators, where we can measure their properties and understand how they fit into the cosmic picture.

7. What are neutrinos telling us?

Ubiquitous, elusive and full of surprises, neutrinos are the most mysterious of the known particles in the universe. They interact so weakly with other particles that trillions of them pass through our bodies each second without leaving a trace. The sun shines brightly in neutrinos, produced in the internal fusion reactions that power the sun. These reactions produce neutrinos of only one kind, but they mysteriously morph into two other kinds on their way to earth. Neutrinos have mass, but the heaviest neutrino is at least a million times lighter than the lightest charged particle.

The existence of the neutrino's tiny nonzero mass raises the possibility that neutrinos get their masses from unknown physics, perhaps related to unification. Detailed studies of the properties of neutrinos—their masses, how they change from one kind to another, and whether neutrinos are their own antiparticles—will tell us whether neutrinos conform to the patterns of ordinary matter or whether they are leading us toward the discovery of new phenomena.

The Birth of the Universe

What started the big bang? How did space, time, matter and energy take the forms that we see today? Can we work backward to unravel the history of the universe?

After the big bang exploded with enormous energy, the universe began the cool-down that has lasted until our own time. The resulting chain of events is a cosmic drama with many acts, dramatic transitions and a host of actors appearing and disappearing along the way. The early scenes played out at unimaginable temperatures and densities, the stage set by the fundamental properties of particle physics. These processes had to be finely tuned to yield a universe capable of forming the galaxies, stars and planets we observe today. Did some undiscovered fundamental laws determine the conditions that allowed us to exist?

To reconstruct the cosmic story, telescopes and space probes detect the relics from the early universe, and particle accelerators recreate and study the extreme physics that characterized the stages of development and the transitions between them. As we begin to understand the cosmic past, we can look to the future of the universe and predict its ultimate fate.

8. How did the universe come to be?

According to modern theories of cosmic evolution, the universe began with a singular explosion, followed by a burst of inflationary expansion. To understand inflation requires breakthroughs in our understanding of fundamental physics, of quantum gravity, and of the ultimate unified theory. Although inflationary conditions are too high in energy to reproduce on earth, we can observe their signatures, transmitted over the eons by their imprint on the relic matter we can still detect from that era.

Following inflation, the conditions of the early universe were still so extreme they could combine elementary particles into new phases of matter. As the universe expanded and cooled, transitions took place as matter changed from one phase to another, like steam condensing into water. Some of these phase transitions may have been the most dramatic events in cosmic history, shaping the evolution of the universe and leaving relics observable today. Cosmic phase transitions could be recreated in high-energy accelerator experiments.

9. What happened to the antimatter?

Experiments teach us that for every fundamental particle there exists an antiparticle. The big bang and its aftermath almost certainly produced particles and antiparticles in equal numbers. However, for as far out in the universe as we can probe, our observations indicate that we live in a universe of matter, not antimatter. What happened to the antimatter? A tiny imbalance between particles and antiparticles must have developed early in the evolution of the universe, or it all would have annihilated, leaving only photons and neutrinos. Subtle asymmetries between matter and antimatter, some of which we have observed experimentally in the laboratory, must be responsible for this imbalance. But our current knowledge of these asymmetries is incomplete, insufficient to account for the observed matter domination.

There must be some other undiscovered phenomenon that makes matter and antimatter behave differently. We may discover it in quarks—or in neutrinos. Its source may lie in the properties of the Higgs boson, in supersymmetry or even in extra dimensions.

The Goal

The nine questions we have asked are the questions that define the science of particle physics today. Answering these questions is the goal of the worldwide program of investigation, driving current and future experiments and the planning for new scientific facilities. In the next section we describe the experiments designed to answer these questions.

III: Tools for a Scientific Revolution

The particle physics community is embarked on an ambitious experimental program that takes the next step toward a revolution in understanding the fundamental nature of matter and energy, space and time. Insights from experiments at particle accelerators, from cosmological observations and from underground experiments have focused the investigation. Further advances require a vigorous program of exploration. Chapter III maps the experimental program onto the questions that define 21st-century particle physics, articulating the strengths of the different approaches and the scientific goals they are designed to achieve.

At the end of this report, we present two tables that list selected facilities of the U.S. program. The primary physics goals of each of these facilities align most directly with the nine questions of this report. In the text of Chapter III, we also discuss certain other facilities that have the potential to make major contributions to the physics presented here.

Einstein's Dream of Unified Forces

Superstrings and grand unification are currently the most promising ideas for fulfilling Einstein's dream of an ultimate theory. To understand string theory requires experimental tests of its predictions of supersymmetric particles and extra dimensions of space. To understand unification requires experiments sensitive to extremely rare particle decays. To confront the discrepancy between the theory of the large and the theory of the small requires a better understanding of fundamental quantum physics.

1. Are there undiscovered principles of nature: new symmetries, new physical laws?

The laws of nature derive from the nature's symmetries; searching for new particles and forces means searching for new symmetries. One such symmetry might be supersymmetry, which predicts that for every known particle there exists a superpartner particle of the same mass. Experiments have not yet detected any of the superpartners; thus, if supersymmetry exists, it must be broken by unknown physics that makes superpartner particles heavy. Superpartner masses may be related to the Higgs field; supersymmetry provides a natural dark matter candidate, the neutralino. Experiments are searching for supersymmetry now; directly at the Tevatron and indirectly at the B-factories Belle and BaBar.

The Tevatron may have enough energy to produce detectable signals of the lightest superpartners. The LHC should have enough energy to produce all or most of the superpartner particles, either directly or through the decays of other superpartners, to determine the pattern of superpartner masses and decays.

A Linear Collider would measure the properties of the superpartners very precisely, showing that they are indeed the superpartners of known particles; it could study the properties of the lightest superpartner (most likely the neutralino) with great precision. Do neutralinos behave like dark matter? Studies of the neutralino at a Linear Collider, combined with precision measurements of other superpartners, would produce a prediction for the cosmic relic density of neutralinos to determine whether the predictions are consistent with the dark matter hypothesis.

Theoretical models for the physical mechanism that breaks supersymmetry are already constrained by data from Belle and BaBar. Future precision studies at Belle and BaBar, as well as from the future hadron B-factories BTeV and LHC-b will allow physicists to disentangle the flavor structure of supersymmetry through subtle changes to decays of B mesons. The MECO experiment will provide

unprecedented sensitivity to the direct conversion of muons into electrons in nuclei; and some models of supersymmetric grand unification predict rates for this process that MECO can observe.

2. How can we solve the mystery of dark energy?

The dramatic discovery of dark energy showed that empty space is filled with a mysterious energy that increases as the universe expands. While Einstein initially proposed a cosmological constant that could explain the dark energy, it is the amount of dark energy that is difficult to understand. The natural source of such a dark energy field, quantum fluctuations of the vacuum, gives a density of dark energy 10^{120} times larger than observed levels.

A far-reaching program is in place to study the properties of dark energy. Measurements of the amplitude and fluctuations of the cosmic microwave background from WMAP, combined with data from worldwide astronomical facilities, especially supernova measurements, suggest that dark energy is consistent with a cosmological constant. Future measurements of supernovae, gravitational lensing and clusters of galaxies from a Large Synoptic Survey Telescope, LSST, and the Joint Dark Energy Mission, JDEM, will reveal definitively whether dark energy behaves like Einstein's cosmological constant or like some new substance that changes with time as the universe evolves.

To determine what dark energy is and why it exists requires connecting the cosmic reality of dark energy to a better fundamental understanding of microscopic quantum physics. At the microscopic scale, physicists have long known that "empty" space is not empty; it is filled by a field that gives quarks and leptons their mass. In the Standard Model, this field is called the Higgs; experiments at the LHC will find the corresponding Higgs particle..

At present, we expect the Higgs to be accompanied by a whole new sector of fundamental physics. This Higgs sector may involve many new particles and interactions. Initial Higgs discoveries will occur at the LHC; a Linear Collider will be essential to explore the landscape of Higgs physics.

Dark energy may have relationships to both supersymmetry and the Higgs sector, implying a new emphasis on the quantum consistency of Higgs physics, including Higgs self-interactions. Such measurements will present additional challenges for the experimental program of the Linear Collider and may provide a foundation to explore the origin of dark energy.

3. Are there extra dimensions of space?

The physical effects of extra dimensions depend on their sizes and shapes, and on what kinds of matter or forces can penetrate them. The sizes of the extra dimensions are unknown, but they should be related to fundamental energy scales of particle physics: the cosmological scale, the density of dark energy, the TeV electroweak scale, or the scale of ultimate unification. It may be possible to infer extra dimensions of macroscopic size from inconsistencies in cosmological observations, or from precision tests of short-range gravitational forces. More likely, the extra dimensions are microscopic, in which case high-energy particle accelerators and cosmic ray experiments are the only ways to detect their physical effects.

The LHC and a Linear Collider will address many questions about extra dimensions: How many extra dimensions are there? What are their shapes and sizes? How are they hidden? What are the new particles associated with extra dimensions? Through the production of new particles that move in the extra space, the LHC will have direct sensitivity to extra dimensions 10 billion times smaller than the size of an atom. A Linear Collider would determine the number, size and shape of extra dimensions through their small effects on particle masses and interactions. There is also a chance that, due to the existence of extra dimensions, microscopic black holes may be detected at the LHC or in the highest energy cosmic rays.

Ultimately particle physics seeks to know if dark energy, dark matter and cosmic inflation are affected by the physics of extra dimensions. Collider data will provide insight into the exploration of these deep connections.

4. Do all the forces become one?

High-energy particle physics experiments are exploring the unification of the weak and electromagnetic forces. Does the unification continue? At the most fundamental level, particles and forces may be related, either through hidden symmetries like grand unification, or through radical physics like superstrings. Essential clues can come from laboratory observations of extremely rare particle decays and other rare processes, as well as from precision measurements at the highest energies. Such breadth of approach is necessary because we do not know where the clues will appear.

- Models of grand unification predict that protons may eventually decay, rendering ordinary matter unstable. The Super Kamiokande detector already has sensitivity to proton decay in the range suggested by models of grand unification. The next generation of proton decay experiments will require larger detectors in an underground laboratory.
- Unification physics represents a natural mechanism to provide Majorana masses for neutrinos, in which case neutrinos are their own antiparticles. This possibility could be verified by a positive signal in the next generation of neutrinoless double beta decay experiments, for example EXO or Majorana, at an underground laboratory.
- The precision measurements of the force strengths at LEP and SLC provided circumstantial evidence for grand unification. Similarly the precision measurement of (super)particle masses at a Linear Collider will permit multiple quantitative tests of grand unification.

Ultimately, unification of all the fundamental forces requires an understanding of quantum gravity and the associated exotic phenomena, such as black hole evaporation. Progress could come serendipitously from a discovery of extra dimensions at the LHC, or of anomalous gravity wave sources with LIGO, or of unexpected events in ultra-high-energy cosmic rays, including cosmic neutrinos.

The Particle World

Physics has revealed that the elementary particles play many roles. The quarks and leptons, the fundamental bits of matter, bind into protons, neutrons and atoms and form the basis of life on earth. The so-called gauge particles give rise to forces, including electricity, magnetism and gravity. Recent discoveries indicate that still more elementary particles make up the dark matter that fills the universe.

In particle physics, elementary particles are the messengers of new phenomena, including new forces and new forms of matter. Quantum mechanics dictates that even hidden dimensions show up as elementary particles. By measuring their properties, physicists can infer the shapes and sizes of the hidden dimensions.

5. Why are there so many kinds of particles?

Physicists have so far identified 57 species of elementary particles. In particular, the Standard Model contains quarks and leptons, grouped into three families that differ only in their masses. Why the pattern of particles is repeated three times with enormous variations in mass but with other properties seemingly identical is an open question. Quantum physics has shown that three families are the minimum necessary to accommodate CP violation in the Standard Model. Such CP violation is necessary for matter to predominate over antimatter in the universe, but its effects observed so far are insufficient to explain this

predominance. The current program of experiments focuses on developing a detailed understanding of the existing patterns and searching for signs that the patterns of the three families are not identical.

The CDF and D0 experiments at the Tevatron are measuring the properties of the top quark to see if its enormous mass gives it a special role in the particle world. The BaBar and Belle experiments at SLAC and KEK are using their data samples, containing millions of b and c quarks, as well as τ leptons, to make precision measurements of the masses and decay modes of all of these objects, in order to look for subtle deviations from the predicted patterns of their decays. The third-generation particles—top, bottom and tau—offer the best hope for discovery, because their large masses allow them to couple most effectively to undiscovered physics.

BaBar and Belle can study only two types of B mesons, bound states of the bottom quark with up or down quarks. However, many theories suggest significant effects in the bound state with the strange quark, B_s. Physicists are currently studying the properties of the B_s meson at the Tevatron. The future hadron B-factories, BTeV and LHC-b, will explore the B_s meson with far greater precision.

Properties of individual quarks are experimentally difficult to study, because they are always bound to other quarks. Lattice Computational Facilities offer great promise for the calculation of the effects of the strong interactions. As an example, lattice calculations will provide sufficient precision to extract quark parameters, such as those that describe flavor mixing, from the experimental data. Experimental studies with CLEO-c will establish and validate the precision of the lattice calculations for use in heavy quark systems.

Neutrinos have opened a surprising new window on the physics of lepton generations, since neutrino masses are not necessary in the Standard Model. The presence of neutrino masses may be telling us something about physics beyond the Standard Model. The decay properties of the light leptons, the electron and the muon, may also hold surprises. The MECO experiment proposes to look for a conversion of a muon to an electron and is sensitive to very-high-mass physics that might affect that process.

6. What is dark matter? How can we make it in the laboratory?

Most of the matter in the universe is dark. Early evidence for dark matter came from the rotation curves of galaxies, which showed that galaxies contain more mass than is contained in the stars. More recently, direct evidence for dark matter has come from the discovery and characterization of gravitational lenses, regions of space where mass bends light. These astronomical constraints do not directly distinguish between nonbaryonic models for dark matter (WIMPs) and other possible ideas involving more massive objects (MACHOs) such as Jupiter-sized planets and mini-black holes. However experiments in the 1990s established that MACHOs do not make an appreciable contribution to the dark matter content of our galaxy.

The tightest constraints on the amount of dark matter in the universe come from cosmological measurements. The frequency and amplitude dependence of the fluctuations in the cosmic microwave background (CMB) measured by WMAP (and in the future by Planck) are sensitive to both the total matter density and the baryon density. The baryon density is also constrained by the nucleosynthesis models of the early universe. All of these methods suggest that normal baryonic matter can only account for a small fraction, about five percent, of the total matter density.

Scientists are measuring the distribution of dark matter in the universe in a variety of ways: (a) by studying the large-scale distribution of galaxies, as with the Sloan Digital Sky Survey (SDSS); (b) by

constraining the dark matter mass power spectrum through weak lensing studies, as by a future Large Synoptic Survey Telescope (LSST) and the Joint Dark Energy Mission (JDEM); and (c) by cataloguing massive clusters of galaxies as a function of redshift, using the Sunyaev-Zeldovitch effect, by the South Polar Telescope and the Atacama Cosmology Telescope.

What is dark matter? Particle physics models suggest that dark matter is either axions (hypothetical new particles associated with QCD), or WIMPs (hypothetical new particles with weak interactions and TeV-scale masses, natural by-products of theories of supersymmetry or extra dimensions). If dark matter particles are relics from the near-total annihilation in the early universe, simple dimensional analysis suggests that the particles originate from physics at the TeV scale. The particle nature of dark matter can be verified by finding the rare events they would produce in a sensitive underground dark matter detector such as CDMS. Such experiments may see products of dark matter particles in our galaxy. Annihilation of TeV-scale dark matter particles might be detected as line radiation in high-energy gamma ray telescopes such as GLAST and VERITAS, or possibly in astrophysical neutrino detectors such as ICE CUBE. Antiparticles produced in these annihilations might also be detectable by AMS. If dark matter particles are much more massive, they might produce signals in the ultra-high-energy cosmic rays.

However, to understand the true nature of dark matter particles, particle physics experiments must produce them at accelerators and study their quantum properties. Physicists need to discover how they fit into a coherent picture of the universe. Suppose experimenters detect WIMPs streaming through an underground detector. What are they? Are they the lightest supersymmetric particle? The lightest particle moving in extra dimensions? Or are they something else?

Searches for candidate dark matter particles are underway at present-day colliders. If these particles have masses at the TeV scale, they will surely be discovered at the LHC. However, verifying that these new particles are indeed related to dark matter will require the Linear Collider to characterize their properties. The Linear Collider can measure their mass, spin and parity with precision. These results will permit calculation of the present-day cosmic abundance of dark matter and comparison to cosmological observations. If the values agree, it will be a great triumph for both particle physics and cosmology and will extend the understanding of the evolution of the universe back to 10^{-10} seconds after the big bang.

7. What are neutrinos telling us?

The discovery that neutrinos have mass opens a window on physics beyond the Standard Model. The Standard Model cannot accommodate neutrino masses without the introduction of new particles, which themselves raise new questions. In fact, the size of the neutrino masses is consistent with expectations from unified theories that require the new particles for the unification itself.

The most pressing question about neutrinos involves how many different kinds there are. Results from the LSND experiment suggest that there may be more than the canonical three families. If so, that would require a major revision of current understanding. The Mini-BooNE experiment, now running at Fermilab, will settle this issue by mid-2005.

Even if there are only three kinds of neutrinos, questions remain. What generates the neutrino masses and what are their values? Are neutrinos their own antiparticles? How do different kinds of neutrinos mix? Answering these questions requires precision measurements of the neutrino masses and mixings. Physicists are now studying neutrino mixing at the SNO, KamLAND, K2K and SuperKamiokande experiments. A big step will occur in 2005, when the NuMI/MINOS program at Fermilab begins to probe nu-mu/nu-tau neutrino mixing in a controlled accelerator experiment. In 2006, the CERN-to-Gran Sasso long-baseline neutrino program will begin. The neutrino beam at JPARC is being developed in

Japan. In the longer-term future, these experiments and their upgrades, possibly using an off-axis beam, or dedicated reactor neutrino experiments may tell us if a measurement of CP violation in the neutrino sector is feasible. Then researchers might use a neutrino superbeam or neutrino factory to search for it. The detector in such an experiment could also search for proton decay, if located deep underground in a facility such as a National Underground Science and Engineering Laboratory.

Accelerator and reactor oscillation experiments measure mass differences. The masses themselves must be determined by different methods. Neutrinoless double beta decay experiments such as EXO and Majorana can be used to measure the electron neutrino mass to ~0.01eV, if neutrinos are their own antiparticles. The observation of neutrinoless double beta decay would have far-reaching consequences, raising the possibility that the matter and antimatter could have transformed to each other in the early universe.

The Birth of the Universe

The understanding of the history and future of the universe is deeply entwined with questions of the fundamental nature of matter, energy, space and time. Today the strong connections between the largest and smallest domains are clearly apparent.

8. How did the universe come to be?

According to current theories of cosmic evolution, the universe begins with an "initial singularity," a point where all known laws of physics break down. This singularity produced a delicately balanced universe, like a pencil so precisely balanced on its point that it stays upright for 14 billion years. How did the universe reach such a state? How did it get to be so old? Why has it not blasted even further apart, or collapsed back on itself?

For the last two decades, the theory of cosmic inflation has offered a compelling explanation of the start of the big bang. According to this theory, an early phase of accelerated expansion gave rise to the balanced universe we see today. Cosmic inflation is the hand that balanced the pencil on its point. As a by-product, it also produced the seeds that evolved into stars, galaxies, clusters of galaxies and other structures in the universe.

Cosmic inflation presents challenges related to the fundamental questions in this report. One possibility is that cosmic inflation originated with a form of dark energy, akin to the dark energy observed today. If so, what kind of matter produced it? Does this form of matter play a role in unification? How does it relate to extra dimensions? Even more radical is the possibility that space and time changed their nature at the start of the big bang. Does string theory smooth the initial singularity? Which model did nature really choose?

At present, measurements of fluctuations in the cosmic microwave background, especially from WMAP, provide the best evidence in favor of inflation. Constraints on cosmic parameters, such as the curvature of the universe, and the nature of the cosmic structure, are in broad agreement with the predictions of inflationary theory. Eventually, measurements of the polarization of the CMB may permit the detection of the signatures of gravitational waves produced during the epoch of inflation, which could provide information about the nature of the scalar field that produced inflation.

After the big bang, the universe expanded and cooled to reach its present state. Along the way, the universe passed through a series of phase transitions in which various particles froze out, as water turns to ice as it cools. These phase transitions drove some of the most important epochs of cosmic history.

For example, a phase transition may be what drove cosmic inflation. Phase transitions might produce "cosmic defects," such as strings and texture and other exotic forms of matter, that could explain ultra-high-energy cosmic rays, dark matter and perhaps even dark energy.

The LHC will illuminate the electroweak phase transition, where most of the known particles acquired their masses. Better understanding of this phase transition will allow scientists to push closer to the big bang itself. Indeed, it is likely that the electroweak phase transition is the ultimate source of the matter-antimatter asymmetry we see in the universe today. Discoveries of new particles and new interactions will illuminate this story and determine if it is correct. Moreover, the account of cosmic evolution must incorporate any discoveries of new symmetries or new dimensions.

Currently, the most intensely studied cosmic phase transition is connected with quantum chromodynamics (QCD), the theory of the nuclear force. During the QCD phase transition, the baryonic matter in the present universe condensed from a plasma-like state of quarks and gluons. The Relativistic Heavy Ion Collider (RHIC) facility at BNL is currently creating collisions of heavy ions to study quark-gluon plasma; the laboratory plans upgrades to enhance these studies. The Lattice Computational Facilities will enable calculations furthering the understanding of the RHIC data and the conditions during this epoch in the evolution of the early universe.

The synthesis of all the elements in the world involves nuclear reactions. Given the temperatures and particle densities in stellar objects and in cataclysmic stellar explosions, these reactions often occur in unstable nuclei. The Rare Isotope Accelerator, RIA, will provide the tool for the terrestrial study of the nuclear reactions that drive these events will help us understand how and where in the universe nature synthesizes the elements.

9. Where did the antimatter go?

A fundamental question in the evolution of the universe is What happened to the antimatter? Matter and antimatter were almost certainly produced equally at the birth of the universe. However, as the soup of the hot early universe cooled, equal amounts of matter and antimatter would have combined and annihilated. Instead, an excess of matter has remained to form the galaxies and stars that constitute the universe. To preferentially remove antimatter in the universe, CP symmetry must be violated, causing antimatter to behave slightly differently from matter. Experimenters discovered CP violation in the neutral K mesons in 1964, and in the B mesons in 2001.

The Standard Model can accommodate the phenomenology of CP violation in quarks, because there are at least three generations of quarks; and because there is mixing between the quark flavors when they interact via the weak interaction. The CP violation measured in the B mesons at BaBar and Belle, along with a wealth of studies on quark flavor mixing over the past 20 years, are all consistent with this phenomenology. However current knowledge of CP violation is incomplete and insufficient by many orders of magnitude to account for the primordial matter-antimatter asymmetry of the universe. Present and planned accelerator experiments are aimed at discovering other sources of CP violation that make matter and antimatter behave differently. It may appear in quarks—or in neutrinos. Its source may lie in the properties of the Higgs boson, in supersymmetry or even in extra dimensions.

CP violation in reactions that change the flavor of quarks is being measured with strange quarks (K meson decays) and bottom quarks (B meson decays). Ongoing and planned experiments include K0PI0 at BNL (K decay); BaBar at SLAC, Belle at KEK (B_d decay), BTeV at Fermilab and LHC-b at CERN (B_d and B_s decay). Pinning down precisely the role of CP violation in the quarks is a critical step in

solving the puzzle of the fate of primordial antimatter. Experiments have so far shown that, by itself, CP violation in quarks from flavor mixing in the Standard Model is probably not the sole source of the matter-antimatter asymmetry observed in the universe. Current and future B physics experiments will be sensitive to sources of CP violation beyond the Standard Model.

The discovery that neutrinos have mass opens up the search for CP violation in lepton reactions. Neutrino mass can, in principle, turn matter into antimatter and back, and can change the balance between them. Experiments are required to discover the role of neutrinos in the antimatter question. The MINOS experiment at Fermilab and reactor-based neutrino oscillation experiments will measure the parameters of neutrino oscillation. If the oscillation parameters are favorable, a neutrino superbeam facility with a large underground experiment will detect CP violation in neutrinos. Such a large detector, if sufficiently far underground, for example at a potential Deep Underground Science and Engineering Laboratory, could also serve as a next-generation proton-decay experiment.

IV: Conclusions

What is the nature of the universe and what is it made of? What are matter, energy, space and time? How did we get here and where are we going?

Particle physics is in the midst of a great revolution. Modern data and ideas have challenged long-held beliefs about matter, energy, space and time. Observations have confirmed that 95 percent of the universe is made of dark energy and dark matter unlike any we have seen or touched in our most advanced experiments. Theorists have found a way to reconcile gravity with quantum physics, but at the price of postulating extra dimensions beyond the familiar four dimensions of space and time.

As the magnitude of the current revolution becomes apparent, the science of particle physics has a clear path forward. The new data and ideas have not only challenged the old ways of thinking, they have also pointed to the steps required to make progress. Many advances are within reach of our current program; others are close at hand. We are extraordinarily fortunate to live in a time when the great questions are yielding a whole new level of understanding. We should seize the moment and embrace the challenges.

V: Summary Tables

The following two tables summarize selected facilities of the U.S. program whose primary physics goals align most directly with the report's nine questions. Other important facilities are included in the text.

LEGEND

The Questions

1 Are there undiscovered principles of nature: new symmetries, new physical laws?
2 How can we solve the mystery of dark energy?
3 Are there extra dimensions of space?
4 Do all the forces become one?
5 Why are there so many kinds of particles?
6 What is dark matter? How can we make it in the laboratory?
7 What are neutrinos telling us?
8 How did the universe come to be?
9 Where did the antimatter go?

Primary US Physics Program of Major Facilities

This table summarizes the physics goals of the major facilities of the US program whose primary physics goals align most directly with the report's nine questions.

	Unification				Particle World			Birth of the Universe	
Question	1	2	3	4	5	6	7	8	9
Tevatron	**X**				**X**				
LHC	**X**	**X**	**X**					**X**	
Linear Collider	**X**	**X**	**X**	**X**		**X**			
NuMI/MINOS							**X**		
ν Superbeams							**X**		**X**
BaBar	**X**				**X**				**X**
BTeV	**X**				**X**				**X**
JDEM		**X**				**X**			
RHIC								**X**	
Proton Decay				**X**					

Primary US Physics Program of Selected Smaller Facilities

This table summarizes the physics goals of selected smaller facilities of the US program whose primary physics goals align most directly with the report's nine questions.

	Unification				Particle World			Birth of the Universe	
Question	1	2	3	4	5	6	7	8	9
Mini-BooNE							**X**		
MECO	**X**				**X**				
Reactor ν Experiments							**X**		
CLEO-c					**X**				
K0PI0									**X**
Neutrinoless Double Beta Decay				**X**			**X**		
SDSS						**X**			
LSST		**X**				**X**			
Underground Dark Matter Detectors						**X**			
WMAP		**X**				**X**		**X**	
CMB Polarization								**X**	
Lattice Computational Facilities					**X**			**X**	
Precision Gravity			**X**						

Committee Members

Andreas Albrecht
University of California at Davis

Samuel Aronson
Brookhaven National Laboratory

Keith Baker
Hampton University
Thomas Jefferson National Accelerator Facility

Jonathan Bagger
Johns Hopkins University

Neil Calder
Stanford Linear Accelerator Center

Persis Drell, Chair
Stanford Linear Accelerator Center

Evalyn Gates
University of Chicago

Fred Gilman
Carnegie Mellon University

Judith Jackson
Fermilab

Steven Kahn
Stanford Linear Accelerator Center

Edward Kolb
Fermilab

Joseph Lykken
Fermilab

Hitoshi Murayama
Institute for Advanced Study, Princeton
University of California, Berkeley

Hamish Robertson
University of Washington

James Siegrist
Lawrence Berkeley National Laboratory
University of California, Berkeley

Simon Swordy
University of Chicago

John Womersley
Fermilab

U. S. Department of Energy
and the
National Science Foundation

October 22, 2003

Professor Frederick Gilman
Chair, HEPAP
Carnegie-Mellon University
5000 Forbes Avenue
Pittsburgh, PA 15213

Dear Professor Gilman:

Recent scientific discoveries at the energy frontier and in the far reaches of the universe have redefined the scientific landscape for cosmology, astrophysics and high energy physics, and revealed new and compelling mysteries. We are writing to ask the High Energy Physics Advisory Panel (HEPAP) to take the lead in producing a report which will illuminate the issues, and provide the funding and science policy agencies with a clear picture of the connected, complementary experimental approaches to the truly exciting scientific questions of this century. The report should elucidate how the questions being asked in particle physics overlap with those being asked by other communities. Further, we are particularly interested in the role that accelerators will play in addressing the important questions and the complementary roles played by other experimental techniques.

We request that HEPAP form a committee that will write a report identifying and addressing the key questions now faced by high energy physics, particle astrophysics and cosmology:

- What are the general methods and technologies that can answer these questions and what is the particular contribution made by particle accelerators?
- What is the current status of scientific efforts in these areas and what are the near-term prospects for advances?
- Explain the connections between various approaches to this research. How can the results from one type of investigation impact the science of another experiment? For example, discuss the interrelation of searches for dark matter.

The membership of the committee should be drawn broadly from the communities in particle physics, nuclear physics, cosmology, astrophysics and related fields that are actively involved in this science and can give independent advice on the relative strengths of the various approaches considered. We would like a brief report which encompasses the most important scientific questions and addresses the issues outlined above in a

summary fashion. We recognize that, given the complexity of interconnections between fields, further studies may be needed to give a more complete picture of these evolving areas. We appreciate your advice on the appropriate "next steps" to follow-up on your report.

We look forward to the creation of this committee in the near future. We would like to have a status report on the work of the committee by the end of 2003, with a final report to HEPAP early in 2004.

We wish you success in this challenging and important endeavor.

Sincerely,

Raymond L. Orbach
Director
Office of Science
U.S. Department of Energy

Michael Turner
Assistant Director
Mathematical and Physical Sciences
National Science Foundation

cc: Ben Weakley, SC-4
Robin Staffin, SC-20
Bruce Strauss, SC-20
Joseph Dehmer, NSF