Physics 662

Particle Physics Phenomenology

February 26, 2002

Physics Beyond the Standard Model

- Supersymmetry ✓
- Grand Unified Theories: the SU(5) GUT ✓
- Unification energy and weak mixing angle ✓
- Supersymmetric SU(5) ✓
- Proton Decay ✓
- Neutrino mass: Dirac and Majorano neutrinos ✓
- Neutrino Oscillations ✓
- Magnetic Monopoles ✓
- Superstrings
- Large Extra Dimensions

- Reference: Donald H. Perkins, Introduction to High Energy Physics, Fourth Edition

Superstrings

"Millennium Madness"

Physics Problems for the Next Millennium

- In 1900 the world-renowned mathematician David Hilbert presented twenty-three problems at the International Congress of Mathematicians in Paris. These problems have inspired mathematicians throughout the last century. Indeed, Hilbert's address has had a profound impact on the direction of mathematics, reaching far beyond the original twenty-three problems themselves.

- As a piece of millennial madness, all participants of the Strings 2000 Conference were invited to help formulate the ten most important unsolved problems in fundamental physics. Each participant was allowed to submit one candidate problem for consideration. To qualify, the problem must not only have been important but also well-defined and stated in a clear way.

- The best 10 problems were selected at the end of the conference by a selection panel consisting of: Michael Duff (University of Michigan), David Gross (Institute for Theoretical Physics, Santa Barbara), Edward Witten (Caltech & Institute for Advanced Studies)

Superstrings

1. Are all the (measurable) dimensionless parameters that characterize the physical universe calculable in principle or are some merely determined by historical or quantum mechanical accident and uncalculable? David Gross, Institute for Theoretical Physics, University of California, Santa Barbara

2. How can quantum gravity help explain the origin of the universe? Edward Witten, California Institute of Technology and Institute for Advanced Study, Princeton

3. What is the lifetime of the proton and how do we understand it? Steve Gubser, Princeton University and California Institute of Technology

4. Is Nature supersymmetric, and if so, how is supersymmetry broken? Sergio Ferrara, CERN (European Laboratory of Particle Physics), Gordon Kane, University of Michigan

5. Why does the universe appear to have one time and three space dimensions? Shamit Kachru, University of California, Berkeley, Sunil Mukhi, Tata Institute of Fundamental Research, Hiroshi Ooguri, California Institute of Technology

Superstrings

6. Why does the cosmological constant have the value that it has, is it zero and is it really constant? Andrew Chamblin, Massachusetts Institute of Technology, Renata Kallosh, Stanford University

7. What are the fundamental degrees of freedom of M-theory (the theory whose low-energy limit is eleven-dimensional supergravity and which subsumes the five consistent superstring theories) and does the theory describe Nature? Louise Dolan, University of North Carolina, Chapel Hill, Annamaria Sinkovics, Spinoza Institute, Billy & Linda Rose, San Antonio College

8. What is the resolution of the black hole information paradox? Tibra Ali, Department of Applied Mathematics and Theoretical Physics, Cambridge, Samir Mathur, Ohio State University

9. What physics explains the enormous disparity between the gravitational scale and the typical mass scale of the elementary particles? Matt Strassler, Institute for Advanced Study, Princeton

10. Can we quantitatively understand quark and gluon confinement in Quantum Chromodynamics and the existence of a mass gap? Igor Klebanov, Princeton University, Oyvind Tafjord, McGill University

Superstrings

Comments on the 10 questions by Professor Andrew Whitaker, QUB, Belfast

1. Are all the (measurable) dimensionless parameters that characterize the physical universe calculable in principle or are some merely determined by historical or quantum mechanical accident and uncalculable?

- The current theory of the basic building-blocks of the universe has to assume their masses, lifetimes and so on. Should there be a more fundamental theory that predicts them?

2. How can quantum gravity help explain the origin of the universe?

- There is as yet no theory of quantum gravity; this is perhaps the major blemish on today's theoretical physics. When this theory is produced, will it, as Hawking suggests, explain the existence of the universe without the necessity of assuming a Big Bang?

3. What is the lifetime of the proton and how do we understand it?

- We have never detected the decay of a proton and so think of it as stable, but many of today's speculative theories predict that it will decay, though with an extremely long lifetime. Experiments with enormous numbers of protons are checking this; will the theories be proved correct?

4. Is Nature supersymmetric, and if so, how is supersymmetry broken? Sergio

- Theories of supersymmetry suggest that all the various forces of nature – electromagnetic, nuclear and even gravitation – may in principle be identical, and claim that this would be seen in experiments at high enough energies. Are they correct? If so, why is the symmetry lost at low energies?

Superstrings

5. Why does the universe appear to have one time and three space dimensions?

- Many of today's speculative theories argue that there are in principle many more dimensions than four (three space and one time) but that several of these dimensions are 'rolled up' so that we don't experience them. Are these theories correct? If so, what causes the 'rolling up'?

6. Why does the cosmological constant have the value that it has, is it zero and is it really constant?

- The cosmological constant appears in Einstein's theory of gravitation, but its value has to be selected. If it is zero, it predicts the expansion of the universe following from the Big Bang. Einstein's original work was performed before the Big Bang was known, and he chose the cosmological constant to be non-zero, so as to prevent the expansion. He later called this his 'biggest mistake'. But is the constant actually precisely zero, or even constant at all?

7. What are the fundamental degrees of freedom of M-theory (the theory whose low-energy limit is eleven-dimensional supergravity and which subsumes the five consistent superstring theories) and does the theory describe Nature?

- Modern string theories, which are hugely popular, describe the basic building-blocks of nature not as particled but as short strings. This avoids some difficulties of previous theories, but do string theories actually tell us anything about nature? If so, what?

(Comments on the 10 questions by Professor Andrew Whitaker, QUB, Belfast)

Superstrings

8. What is the resolution of the black hole information paradox?

- When a particle in a quantum-mechanically pure state disappears into a black hole, its state changes to a thermal one; it now has a particular temperature. This constitutes a fundamental violation of the laws of quantum theory. How does it occur?

9. What physics explains the enormous disparity between the gravitational scale and the typical mass scale of the elementary particles?

- Mass and energy are linked by Einstein's equation . But typical gravitational energies are immensely lower than the values of for typical elementary particles. Why?

10. Can we quantitatively understand quark and gluon confinement in Quantum Chromodynamics and the existence of a mass gap?

- We believe that the proton consists of three quarks, but that it is impossible to extract a free quark. The theory of quantum chromodynamics suggest that this is because, as the distance between two quarks increases, the force of attraction between them increases, rather than decreasing as for gravitation or electrostatics. But can this theory be made rigorous? Can it explain the masses of the various types of quark?

(Comments on the 10 questions by Professor Andrew Whitaker, QUB, Belfast)

Superstrings

- Unify all fundamental interactions including gravity
- Point-like interactions result in divergences
- Divergences are cured by replacing point particles by strings
- These strings are expected to have lengths of order of the Planck scale:

$$l_P = \frac{\hbar}{M_P c} = 1.6 \times 10^{-35}\ \mathrm{m}$$

where the Planck mass is

$$M_P = \sqrt{\hbar c / G_N} = 1.2 \times 10^{19}\ \mathrm{GeV}$$

- Elementary particles are different modes of oscillation of the loop of the string

Superstrings

1985- it seemed clear that there are five different superstring theories, each requiring ten dimensions (nine space and one time),

The five theories,

- type I,
- type IIA,
- type IIB,
- E8 X E8 heterotic (HE, for short),
- SO(32) heterotic (HO, for short).

The type II theories have two supersymmetries in the ten-dimensional sense, while the other three have just one.

The type I theory is based on unoriented open and closed strings, whereas the other four are based on oriented closed strings

The IIA theory is special in that it is non-chiral (i.e., it is parity conserving), whereas the other four are chiral (parity violating)

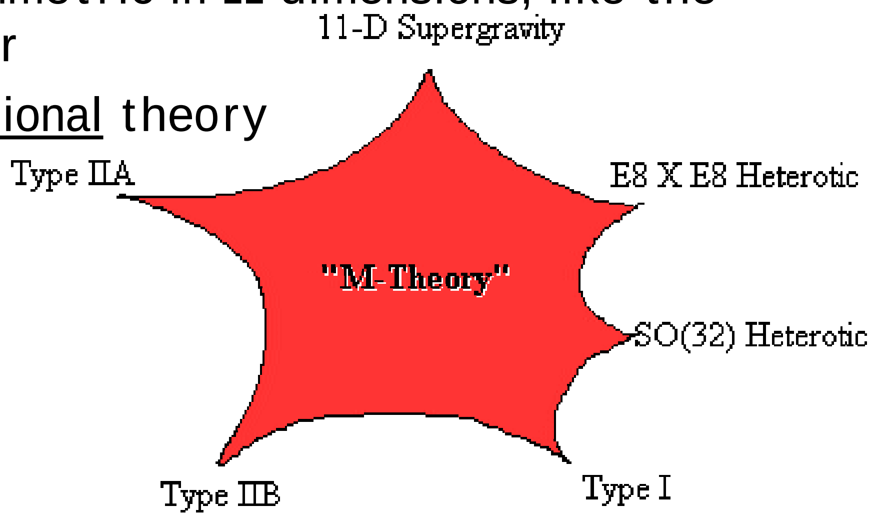
Superstrings

- The ten dimensions of string theory include the usual four dimensions plus others than are curled up, perhaps to dimension of the Planck scale, but some might be large.

- Gravity is unified with other forces, supersymmetric particles are predicted, and divergences cancel.

Superstrings

- M Theory
  - 1994 revolution (E. Witten)
  - The five string theories are shown to be different approximations of the same theory
  - This unique theory is supersymmetric in 11 dimensions, like the 11-D sypergravity of past favor
  - There is one, unique, 11 dimensional theory



- Three radical ideas
  - Supersymmetry
  - Extra space-time dimensions
  - Extended objects

Large Extra Dimensions

- Some of the extra dimensions could be quite large
- The experimental limits on the size of extra dimensions are not very restrictive
  - to what distance has the r^{-2} force law been measured?
  - extra dimensions could be as large as 0.1 mm, for example
  - experimental work is underway now to look for such large extra dimensions

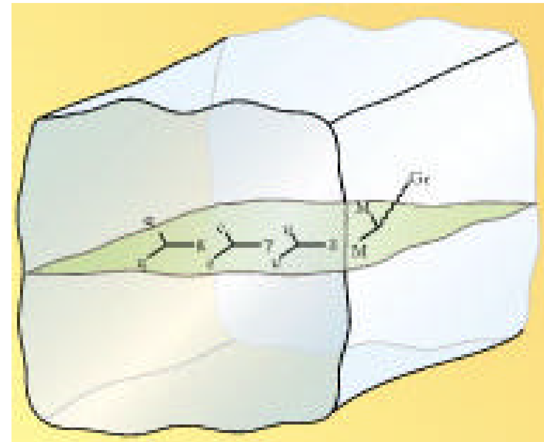
Large Extra Dimensions

(see "Large Extra Dimensions: A New Arena for Particle Physics", Nima Arkani-Hamed, Savas Dimopoulos, and Georgi Dvali, Physics Today, February, 2002)

An exciting new idea explains the hierarchy problem

- In addition to the three infinite spatial dimensions we know about, it is assumed there are n new spatial dimensions of finite extent R.
- The space spanned by the new dimensions is called "the bulk."
- The particles of the standard model
  - quarks, leptons, and gauge bosons
- all live in our familiar realm of three spatial dimensions, which forms a hypersurface, or "3-brane" within the bulk.
- The propagation of electroweak and strong forces is then confined to the 3-brane.

Large Extra Dimensions



- Gravity is different:
  - Gravitons propagate in the full (3 + n)-dimensional space
- Addressing the hierarchy problem:
  - At distances less than R, gravity spreads in all the 3 + n spatial dimensions, and therefore the gravitational force falls like r - (2 + n) with increasing separation r.
  - Thus gravity's strength, relative to the electric force, is rapidly diluted with increasing separation--and just as rapidly augmented with increasing proximity.
  - Of course, when r exceeds R, the gravitational force reverts to its normal r-2 falloff, there being no longer any extra-dimensional space in which to spread out.

(see Large Extra Dimensions: A New Arena for Particle Physics, Nima Arkani-Hamed, Savas Dimopoulos, and Georgi Dvali, Physics Today, February, 2002)

Large Extra Dimensions

- In superstring theory, we see extra dimensions not much larger than the 10^{-33} cm Planck length.

- Suppose the extra dimensions are much larger--perhaps even macroscopic.

  – Matching the Newtonian and higher-dimensional expressions for the gravitational force at r »R, we get

$$M_{Pl}^2 = M_*^{2+n} R^n$$

  – where M_* is the true energy scale of gravity in 3 + n dimensions.

  – If we now assume that $M^* \approx M_{ew}$, we find that $R \approx 2 \times 10^{(32/n)-17}$ cm.

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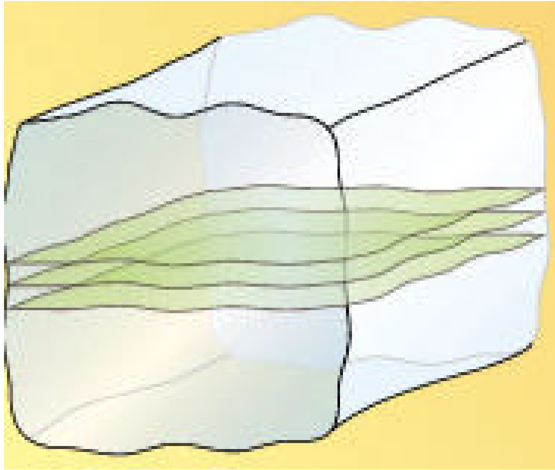
Large Extra Dimensions

- If there were only one extra dimension (n = 1), its size R would have to be of order 10^{10} km to account for the weakness of gravity.
  - An extra dimension that large would long ago have made itself obvious in the dynamics of the Solar System.
- But two equal extra dimensions would be on the order of a millimeter in length.
  - That happens to be close to the limit of the Cavendish-type experiments that have checked Newtonian gravity at short range.
- As the number of the new dimensions increases, their size gets smaller.
  - For six equal extra dimensions, the size is only about 10 fermi.
  - Most exciting is the n = 2 case of two submillimeter-sized dimensions, which is the subject of active search by several tabletop Cavendish experiments.

(see Large Extra Dimensions: A New Arena for Particle Physics, Nima Arkani-Hamed, Savas Dimopoulos, and Georgi Dvali, Physics Today, February, 2002)

Large Extra Dimensions



- Perhaps our brane is not alone in the bulk, but there are others as well
- The physics on those other branes
  - the particles that inhabit them, and their forces and symmetries

  may be different from ours.
- Nevertheless, their presence would influence physics on our brane.
  - That's because branes are sources for bulk fields, much as charges are sources for the electric field. The values of these bulk fields at the location of our brane may determine the parameters of our standard model
    - for example, the electron mass,
    - the Cabbibo angle,
    - and the electroweak-mixing angle.
  - Conversely, these parameters probe the location of those other branes in the bulk.

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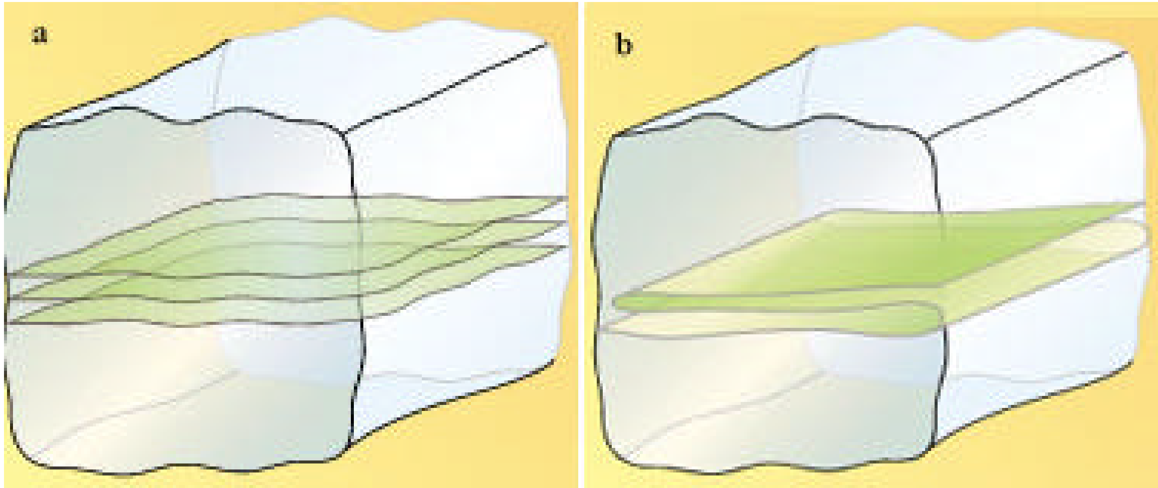
Large Extra Dimensions

- It might even be that 3-brane regions separated from us by short distances across the bulk are not really separate branes with fundamental parameters different from ours.
- They could conceivably be separate folds of our own 3-brane.
- It might be that the astrophysical and cosmological anomalies we attribute to "dark matter" are actually weak manifestations, across short intervals of the bulk, of ordinary matter in adjacent folds of our 3-brane.



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Large Extra Dimensions

Theoretical issues

- What stabilizes the size of the extra dimensions?
- If quantum gravity really gets strong near a TeV, why don't virtual black holes give rise to nearly instantaneous proton decay?
- What does this framework do to the predicted supersymmetric unification of the electroweak and strong coupling strengths near M_{Pl}

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