INTRODUCTION TO SUPERSYMMETRY AND SUPERSTRING THEORIES[1]

ABSTRACT

In this talk I introduce for the non-specialist the fundamental concepts that provide the basis for the radically new developments in theoretical particle physics known as "supersymmetry" and "superstrings."

1. A SUPER-REVOLUTION IN FUNDAMENTAL PHYSICS?

During the last few years there has been a super-revolution going on in physics. Much of the public has become aware of the existence of high temperature "superconductors." These marvelous materials hold the promise of revolutionizing the technological basis of our society. Their existence is such that industrial preeminence and economic benefits in the twenty-first century could well accrue to the country or countries that discover and develop products based on superconductor technology.

In nineteen-eighty seven another super event in physics took place. A rarely observed supernova explosion, SN 1987A, took place. The explosion of stars signified by supernovae are so uncommon that the last recorded such close event was in 1054 A. D. Physicists have developed theories which attempt to describe the cataclysmic explosions that occur when stars collapse. The event last year marked the first time that modern fairly detailed observations could be made to compare with theoretical predictions.

There is yet another super-topic that is stirring great interest in the scientific community of physicists. This is the topic of "superstrings." From the practical viewpoint, it is unlikely to have the impact of the two proceeding topics. But at the fundamental level, it is in some ways the most astounding of the super-topics in

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physics today. It appears as though a theory that was a dream held by Einstein for the last forty years of his life has been created. This goal, which he unsuccessfully sought, was commonly known as the "unified field theory." Superstrings seem to give not only a single such theory but the possibility of constructing many such theories. As a by product, superstrings also seem to permit for the first time the hope of constructing mathematical models where the effects of quantum mechanics and gravitation can simultaneously be described in a mathematically consistent way. The base for this advance is so radical that it requires that we abandon a concept that has served extremely well for over twenty-four hundred years in considering the nature of our universe. Through out this time, the basic "stuff" out of which our universe was constructed was thought to be to point-like structures that we call fundamental particles.

These fundamental particles are suppose to have no smaller divisible parts. One can imagine a fundamental particle as a ball or dot with no measurable size, in other words as the mathematical concept of a point. In 1808, John Dalton proposed that atoms were these fundamental particles. The very word atom is derived from the Greek *atomos* or Latin *atomus* which translate as indivisible. We now know that there are protons, neutrons and electrons inside of atoms. Up to the nineteen thirties we thought these were the fundamental particles. This turns out to be incorrect again. The electron does appears to be fundamental. But curiously enough nature seems to have also provided two extra copies of the electron (known as the muon and taon) and three other closely related particles (neutrinos). All of these are collectively called leptons. However, protons and neutrons are not fundamental. Both appear to be made up of "quarks." Quarks were proposed in 1964 by M. Gell-Mann and G. Zwieg to explain a certain regular pattern observed among protons, neutrons and related particles. (This pattern is very much like that observed in the table of chemical elements.) To explain the presently observed pattern there must be eighteen different quarks.

Both quarks and leptons behave as if they are spinning about an axis of revolution at the same rate...$\frac{1}{2}\hbar$. We call such spinning objects fermions and their existence is very important. The fact that the electron is a lepton is the basic reason why the periodic table takes its observed form. The familiar saying, "No two objects can occupy the same space at the same time," is true because objects contain fermions. Fermions obey the *Pauli Exclusion Principle* and this is what prevents two identical electrons from being at the same place at the same time.

This also keeps them from falling to the lowest energy levels in atoms. However, not all fundamental particles spin at the same rate. This brings us to the another group of particles. The quarks and leptons are the basic "stuff" of matter. But something has to hold aggregates of these together to form nuclei, atoms, molecules, compounds, cells, etc. all the way back to people and the things they see around them.

Fundamental particles are held in aggregates by forces. But one of the remarkable things we have discovered is that forces (acting at the fundamental level) arise due to "force carrying particles" or "gauge particles." We must recount what are the fundamental forces in nature. There are four such fundamental forces. The best known is perhaps gravitation. We are all familiar with this force from everyday experiences. The next most familiar force is electromagnetism. This is the force that exist between charged objects or magnets for instance. the two remaining forces are less familiar. They are the "weak" and "strong" nuclear forces. Although less familiar, there are well known examples of the effects of these forces. The uncontrolled release of energy in the explosion of a hydrogen bomb is due primarily to the strong nuclear force. On the other, the natural radioactivity of radium is due the weak nuclear force. The force carrier of the electromagnetic force is called the "photon." For the gravitational force there is the "graviton." There are three known force carriers of the weak force, the "W^+-boson, W^--boson, and Z^0-boson." The actual carriers of the strong force go by the name of "gluons" and there are eight of them. All of the gauge particles are spinning also but with some differences. The photon, W^+-boson, W^--boson, Z^0-boson, and gluons are all spinning at a rate of one times $\hbar$. This is twice as fast as the electron. The graviton spins at a rate that is four times as fast as the electron, i.e. two times $\hbar$. Particles that spin at integers times $\hbar$ are called bosons. Bosons do not obey the *Pauli Exclusion Principle*. If electrons were bosons there would be no periodic table of elements because the electrons would all fall to the lowest energy levels!

There are other ways in which the world of fundamental particles differs from our everyday experiences. One of the surprises that physicist discovered when they first began to study atoms was that Newton's Laws do not apply to tiny objects! In fact, it is not even accurate to describe tiny objects as particles because sometimes tiny "particles" exhibit wave-like behavior. This true whenever the wavelength λ ($\lambda = \frac{2\pi\hbar}{mv}$) associated with a particle becomes comparable to the dimensions of its surroundings. Among other things we cannot simultaneously measure their speed and location. The laws of Newtonian mechanics must be replaced by the laws of quantum mechanics which do describe the dynamics of “wavicles” or “partaves.” (We use these fictitious words to emphasize that is not possible think in terms of the naive everyday concepts.) But this is accomplished by introducing a “wavefunction” Ψ associated with each type of particle. Newton’s second law $\vec{F} = m\vec{a}$ is replaced by equations which govern the evolution of the wavefunction.

The final problem encountered is that when objects move near the speed of light, time and space are no longer separate. The laws of physics once again depart from our everyday experiences. This is the realm of Einstein’s theory of special relativity. Time slows down and lengths decrease for rapidly moving object. The faster an object moves the greater its mass appears to be. But nothing can move faster than the speed of light. In order to move at the speed of light an object must be massless. Interestingly enough the graviton and gluons are massless, so they can travel at the speed of light. Since fundamental particles are small it is often the case that they travel at near the speed of light. Therefore, all the the highly unusual effects of special relativity are important and must be properly taken into account. When this is done for a quantum mechanical theory, we enter the area of “relativistic quantum field theory.” Here we replace the concept of the Schrodinger wavefunction by the more general concept of a quantum field. Particles can now be created, converting energy into mass according to the famous equation: $E = mc^2$. Similarly, particles can be destroyed turning their mass back into energy.

As there is a set of equations which describe the interactions of charges and currents, there is also a set which describes the interactions of matter fields and gauge fields. This set is known as “the standard model.” This theory describes electromagnetic, strong and weak forces with admirable simplicity and accuracy. It includes the effects of quantum mechanics and special relativity...but not gravity!

2. WHAT IS SUPERSYMMETRY?

As we have just discussed, the fundamental particles in nature can be broadly divided into two groups, bosons and fermions. Bosons are responsible for mediating the forces and fermions make up the matter upon which the forces act. Mathematically the dynamics of these two types of object are very different. Typically the equations which govern bosons are like Maxwell’s equations of electromagnetism or some generalization thereof. For instance, the equations of Einstein’s theory of general relativity are such a generalization. Likewise, the equations which govern fermions are similar to the Dirac equation.

Now we can pose an interesting question, "Why are all of the force carriers bosonic while all of the matter upon which the forces act are fermionic?" In other words, "Is it possible to have fermions act as carriers of forces and have bosons as the matter upon which forces act?" These are purely theoretical questions because there is no presently available experimental evidence of fundamental fermionic force carriers or fundamental bosonic matter. However, theoretical particle physicists have been asking these questions and studying their consequences for over a decade. This is the arena of "supersymmetry." A theory in which matter can be bosonic or fermionic and force carriers can be bosonic or fermionic is said to have a supersymmetry. The suffix symmetry is used to connote the balanced way in which the two types of particles (bosons and fermions) would now participate in the theories. A supersymmetrical model was first discovered in nineteen seventy-two by two soviet physicists, D. Volkov and V. P. Akulov. Independently, the general principle of supersymmetry was discovered by J. Wess and B. Zumino about a year later in Europe. In order to have supersymmetry, particle must come in pairs separated by one half a unit of spin.

Notice that in the real world we have only discovered fields of spins two (graviton), spin one (photons and gluons) and spin one half (quarks and leptons). But in a hypothetical world with supersymmetry, we are free to imagine using all spins of two down to zero! After all why should we be partial to particular spins. This implies that if our world is in a sense supersymmetric, there may be a lot of particles that we simply have not discovered. For each particle that we know about there would be an undiscovered "superpartner." For example, the super partner of the spin one photon would be a spin one half "photino." Or the superpartner of the spin one half electron would be a spin zero "selectron". Similarly, the superpartner of a spin one half quark would be a spin zero "squark." The spin two graviton would have a spin three-halves superpartner, the "gravitino." If all of these extra objects exist, why haven't seen them? If our present view is correct, it is because none of the present generation of accelerators is powerful enough. That is why the "superconducting supercollider" has been proposed to be built in the nineteen nineties. It is hoped that with such a powerful particle accelerator, we will have enough energy to produce the effects that will indicate the presence of superpartners.

2. WHAT ARE SUPERSTRINGS?

Above we described the standard model and how it enables us to make predictions about the behavior of all known matter obeying the laws of special relativity and quantum mechanics and interacting with all of the forces except gravity. This drawback was recognized long ago. Some attempts were made to include gravity into this model. But these were disastrous. It was found that the model lost all predictive power due some mathematical difficulties known as divergences.

From an esthetical viewpoint, the fact that gravity was not welded together with other forces in nature was a source of disturbance to Albert Einstein. He thought that somehow matter, gauge fields and gravity ought to be all combined in a "unified field theory." After 1915 having developed the theory of general relativity to describe the force of gravity, he spent the last forty years of his life trying to develop a consistent unified field theory of nature. To go beyond Einstein it appears we must enter the world of superstrings.

If superstrings are necessary, then why have we always had success for approximately two millenia using the notion of the point particle? Let us consider the scale of size that will be important to strings. The size of strings is characterized be a new fundamental constant in nature, α'. Some previous known constants include the speed of light c and Planck's constant $2\pi\hbar$. In a convenient set of units α' is 10^{-35} meters. This number is so incredibly small that we need something with which to compare. The typical atomic nucleus is approximately 10^{-15} meters. A typical person is approximately 1 meter, give or take a factor of two. In other words, the difference in scale between a string and a nucleus is greater that the difference in scale between a nucleus and a person! The very limit of our observation presently permit us to "see" objects on the size of 10^{-19} meters. So strings are almost unimaginably small.

String theorists are often asked is, "What is a superstring?" Let us first ask, "What is the picture that a physicist has in mind when he or she thinks of a particle? The simplest picture is to visualize a dot (see fig. 1). Since the notion of a point in geometry should correspond to a particle, we have to imagine a dot so small that it has no size at all! A moving dot traces out a continuous curve called a line segment. It may be curvy or straight. This line segment is a string! As a particle is a dot of vanishing size, a string has no thickness. This concept of the string was first introduced by Y. Nambu. Redoing all of physics with strings is very, very difficult because the notion of the point particle has crept into almost all of our understanding and formulation of physics! Even the mathematics needed for strings is more complicated than that for point particles.

Strings can also do things that particles cannot. If the two ends of a string are joined together and it moves off in some direction it will then sweep out a tube (see fig. 2). A string which doesn't join at its two ends and moves along will sweep out a surface (see fig. 1). We see that there are two kinds of strings; open (ends not joined) and closed (ends joined). Real strings can do one other thing that a dot cannot. A string can *sing*! It can vibrate in normal modes to produce notes. For these tiny superstrings the same must be true, but the way in which these different "notes" would manifest themselves at the level of the nucleus is as the appearance of different particles. The vibrations of the superstrings appear as particles! A superstring is one which has a supersymmetry in the particles that appear as its vibrational normal modes.

The most intense study is presently being undertaken of the so-called "heterotic" string by D. Gross. J. Harvey, E. Martinec, and R. Rohm. Among the things that went into this discovery was that closed strings can support vibrations that move to the left and are totally different from those that move to the right and still be mathematically consistent. We may envision a closed string with a "dimple" on its side (see fig. 3). As the closed string with the dimple (wave pulse) moves, it sweeps out a tube. The closed string can support three types of wave pulses. In the first diagram we see a "standing wave." The string moves down the tube and the pulse stays at the same "location" relative to the side of the tube. In the second diagram, we see a "right-moving wave." As the string moves down the tube, the pulse winds around the tube in a clockwise direction. The final diagram contains a picture of a "left-moving wave." The string moves down the tube and the pulse winds around the tube in a counter-clockwise direction. Modern four dimensional superstrings use all three types of pulses. Furthermore, as particles can scatter off of one another, string can also have interactions. For example, two free open strings ,S_1 and S_2, (see fig. 4) can interact by forming a closed tube (string for a period of time and then becoming free again. Similarly, two closed closed strings C_1 and C_2 can join together to become a single closed string C_3 (see fig. 5).

Now the reason that some particle physicists are so excited about superstrings began some time ago. In 1975, J. Scherk and J. Schwarz noticed that closed string theories always predicted the existence of a force carrying particle with spin two. As we have discussed, there is such a force carrying particle in nature; the graviton. In the early eighties, M. Green and J. Schwarz revived interest in the subject when they showed that the mathematical problems called divergences do not occur in the string with supersymmetry (i.e. a superstring). This was a remarkable result because these are present in the standard model if one tries to include gravity. At this stage we see the first major step in achieving Einstein's dream. For the first time it seems as if it is possible to include the effects of gravity and quantum mechanics in a self-consistent way. Ultimately this will allow us to study questions about the behavior of matter and energy that we simply cannot even address now. For instance, new insights may be gained on "black holes" and "quasars." String theory may alter our understanding of the creation and evolution of the universe.

Superstring have a lot of properties that we find surprising at present. For instance, superstrings do not play favorites with spin. By this we mean that a superstring requires the existence of all possible spins for its mathematical consistency. This corresponds to an infinite number of fundamental particles. This should be expected because a perfect vibrating string is capable of producing an infinite number of notes. We have a fundamental tone and all of its harmonics. But only those particle with spins less than two are important for most of the physics of our universe. There are other problems known as anomalies which string miraculously evade. Should string theory prove to correct, then our shift of view from particles to strings may one day be viewed as monumental a change as the shift from the Ptolemaic view to the Copernicean view of the earth and its place in the heavens. We particle theorist have a major task to understand these promising new theories and we have just barely begun.

By possessing many different ways of vibrating, the superstring can describe many different particles in a *unified* way... as was Einstein's goal.