SUPERSYMMETRY

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Abstract

The motivations for supersymmetry are presented, superpartners are defined, and current searches for supersymmetry are described.

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SUPERSYMMETRY

Supersymmetry is a space-time symmetry, an extension of the symmetries of translations, rotations, and boosts. Supersymmetry has played an important role in a broad range of modern developments in physics and mathematics. In particle physics, it is conjectured to be a fundamental symmetry of the elementary particles and provides the framework for many attempts to unify the electromagnetic, weak, strong, and gravitational interactions. In this context, supersymmetry predicts as of yet undiscovered partner particles for each of the known elementary particles. The search for these supersymmetric particles and other evidence for supersymmetry is currently the subject of intense research activity spanning a variety of disciplines in particle physics, astrophysics, and cosmology.

NEW SPACE-TIME SYMMETRY

Symmetries play an essential role in descriptions of the physical world. Among the most fundamental of these are space-time symmetries. These include translations, rotations, and boosts. Translations shift an object, such as a particle or system of particles, from one place and time to a different place and time. Similarly, rotations transform an object into the same object rotated in three-dimensional space, and boosts transform an object into the identical object with a new velocity. Rotations and boosts together form Lorentz symmetry. When supplemented by translations, the full set of symmetries is called Poincare symmetry. All known physical laws are invariant under these symmetries. Under general assumptions, stated precisely in the Coleman-Mandula theorem, Poincare symmetry is the maximal space-time symmetry that transforms particles into identical particles.

Supersymmetry is a new space-time symmetry. It extends Poincare symmetry without violating the Coleman-Mandula theorem by transforming particles into particles that differ from the original by one-half unit of spin. Spin is an inherently quantum mechanical property of all elementary particles. It has no classical analogue, but may be thought of as internal angular momentum. In four dimensions, all particles have integer or half-integer spin. Those with integer spin, such as the photon, are bosons. Those with half-integer spin, such as the electron, are fermions. Supersymmetry therefore transforms bosons into fermions and fermions into bosons. All other particle properties, such as mass and charge, are preserved under supersymmetry transformations.

Rudolph Haag, Jan Lopuszanski, and Martin Sohnius showed in 1975 that supersymmetry is the maximal possible extension of Poincare symmetry. If supersymmetry is discovered, all mathematically consistent space-time symmetries will have been realized in nature.

SUPERPARTNERS

Because supersymmetry transforms particles into distinct particles with different spin, it predicts the existence of as of yet undiscovered supersymmetric partners, or superpartners, for all known particles. (The possibility that some of the known particles are the superpartners of other known particles is excluded by comparing basic properties.) The Standard Model of particle physics describes all known fundamental particles and their interactions. It includes matter fermions, such as the electron, neutrino, and quarks, and interaction bosons, such as the photon, which transmit forces. These and their superpartners are listed in Table I. Superpartner names are derived from their Standard Model counterparts by appending the suffix ”-ino” for supersymmetric fermions and adding the prefix ”s-” for supersymmetric bosons. Symbolically, they are denoted by adding tildes ($\sim$) to the symbols for their Standard Model partners.

Exact supersymmetry is not realized in nature — for example, there is no boson with electric charge -1 that has a mass equal to that of the electron’s. Therefore, if it exists in nature, supersymmetry must be broken. In theories with softly broken supersymmetry, the equality of masses of supersymmetric pairs is broken, but the charges and other quantum numbers of superpartners remain identical. Such theories possess a number of important virtues and are the most widely studied supersymmetric theories. General indirect evidence suggests that superpartners, if they exist, should have masses not far beyond those of Standard Model particles. Various supersymmetric theories make specific predictions for the superpartner masses, but these predictions vary widely from theory to theory.

UNIFICATION OF FORCES

Although there is no direct evidence for supersymmetry, there are a number of indirect motivations. Among these, two are related to the unification of forces and are of special significance.

The first motivation stems from the observed weakness of gravity relative to the other forces. An understanding of this discrepancy is among the most important challenges for those seeking

TABLE I: Standard Model particles and their conjectured superpartners. Masses are given for the known particles in units of GeV, approximately the proton mass. For particles not yet discovered, approximate lower bounds on masses are listed.

Standard Model Particles			Superpartners		
	Spin	Mass (GeV)		Spin	Mass (GeV)
Matter Fermions					
e electron	1/2	0.0005	$\tilde{e}$ selectron	0	> 95
ν neutrino	1/2	$< 10^{-7}$	$\tilde{\nu}$ sneutrino	0	> 41
q quarks	1/2	$0.004 - 174$	$\tilde{q}$ squarks	0	> 200
Interaction Bosons					
γ photon	1	0	$\tilde{\gamma}$ photino	1/2	> 37
W	1	80	$\tilde{W}$ Wino	1/2	> 68
Z	1	91	$\tilde{Z}$ Zino	1/2	> 37
g gluon	1	0	$\tilde{g}$ gluino	1/2	> 200
G graviton	2	0	$\tilde{G}$ gravitino	3/2	?
h Higgs boson	0	> 114	$\tilde{h}$ Higgsino	1/2	> 37

a unified description of the fundamental interactions. That gravity is weak may be understood in several ways. For example, the electromagnetic repulsion between two electrons is roughly 10^{42} times stronger than their gravitational attraction. Alternatively, one may determine the mass required for a hypothetical particle with unit charge to experience gravitational and electromagnetic interactions equally. This is the Planck mass, and it is approximately 10^{19} GeV. From this point of view, gravity is weak because the masses of even the heaviest elementary particles, such as the W and Z gauge bosons, are so far below the Planck mass. In this guise, the puzzle of the weakness of gravity is also known as the gauge hierarchy problem.

The gauge hierarchy problem is especially severe in quantum field theories like the Standard Model, where the classical masses of particles are modified by contributions from quantum effects.

In the Standard Model, some of these quantum contributions are naturally of the order of the Planck mass, and the weakness of gravity then results from an inexplicable and nearly exact cancellation between enormous classical and quantum contributions to yield relatively tiny observed physical masses.

Supersymmetry solves the gauge hierarchy problem by introducing superpartners that generate additional quantum mass contributions. For exact supersymmetry, these contributions exactly cancel the quantum corrections of the Standard Model. Physical masses are then given solely by their classical values, and no fine-tuned cancellations are required. In softly broken supersymmetry, the quantum corrections do not cancel exactly, but are of the order of the superpartner masses. In these theories, large cancellations are therefore also avoided, provided the superpartner masses are not substantially larger than typical masses in the Standard Model.

Supersymmetry is also motivated by the desire to unify the other three forces. Although the strengths of the electromagnetic, weak, and strong forces are roughly similar, especially when compared with gravity, they nevertheless differ, providing another impediment to attempts to unify forces. The observed coupling strengths of these three forces are modified at very short distances, where effects similar to the screening of electromagnetic charge are eliminated. However, in the Standard Model, these interaction strengths differ even at short distances. In supersymmetric models, though, superpartners modify these screening effects. When these are removed, the strengths of the electromagnetic, weak, and strong forces agree with remarkable precision at very short distances. This quantitative result is indirect evidence for supersymmetric grand unified theories (GUTs), in which the electromagnetic, weak, and strong forces are described by one underlying interaction. The simple elegance of these theories provides further impetus for the study of supersymmetry.

CURRENT SEARCHES AND FUTURE PROSPECTS

Although significant, indirect evidence is no substitute for the discovery of superparters or other supersymmetric effects. The search for supersymmetry is currently an area of intense activity and may be divided into three broad categories.

The first category includes searches for superpartners in high- energy collider experiments. Such searches have been conducted at all major colliders, with the most sensitive searches to date conducted at the Large Electron Positron (LEP) collider at the European Laboratory for Particle

Physics (CERN) in Geneva, Switzerland, and the Tevatron proton–anti-proton collider at Fermilab in Illinois. No evidence for supersymmetry has been found, and these searches have yielded only lower limits on superpartner masses. While these lower bounds depend on the particular supersymmetric theory being considered, characteristic limits are listed in Table I. Limits for specific theoretical models are updated annually by the Particle Data Group Collaboration in the Review of Particle Physics.

In the near future, the Large Hadron Collider (LHC) at CERN will collide protons with energies far above those accessible at present. The LHC will copiously produce superpartners that interact through the strong interaction, namely, squarks and gluinos, unless they are very heavy. The discovery reach of the LHC is well above 1,000 GeV for squark and gluino masses. For the other superpartners, the reach is somewhat less. Nevertheless, given that a supersymmetric explanation for the weakness of gravity requires superpartner masses not far above those of the Standard Model, the LHC is expected to provide a stringent test of many of the most attractive supersymmetric theories.

Searches for supersymmetry are also underway in a variety of low-energy particle physics experiments. Although such experiments cannot produce superpartners, they may be sensitive to the fleeting effects of short-lived superpartners that may exist as a result of Heisenberg's uncertainty principle. The most promising of these experiments include those that are extremely sensitive to small deviations, such as those measuring the magnetic dipole moment of the muon, and those searching for phenomena absent in the Standard Model, such as searches for electron-muon transitions, electric dipole moments, and rare decays.

Finally, in many supersymmetric theories, the lightest superpartner is stable and interacts weakly with ordinary matter. Such particles are natural candidates for dark matter, the mass responsible for the observed binding together galaxies and galaxy clusters, which has not yet been identified. Searches for dark matter are also, then, searches for superpartners, and many current and future dark matter detection experiments are sensitive to supersymmetric dark matter.

If discovered, supersymmetry will drastically modify the understanding of the microscopic world. Measurements of superpartner masses and properties from the LHC and other experiments will favor some supersymmetric theories while excluding others, and provide new insights into attempts to unify the fundamental interactions in grand unified theories or superstring theory.

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