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ENCYCLOPEDIA ARTICLE

Weakly interacting massive particle (WIMP)

A hypothetical elementary particle that might make up most of the matter in the universe, and that is also predicted to exist in supersymmetry theory. Most matter is detected only through its gravitational effects; this "dark matter" has not been observed to emit, absorb, or reflect light of any wavelength. The total amount of dark matter appears to be approximately ten times as great as all the ordinary matter in the universe, and about one hundred times as great as all the visible matter. The nature of the dark matter is not yet known, although many experiments are under way to try to discover it directly or indirectly. See also: Cosmology; Universe

Almost all the currently available data in elementary particle physics can be accounted for by a theory called the standard model, in which matter is made of quarks (the building blocks of protons and neutrons) and leptons (including electrons and neutrinos), while the strong, weak, and electromagnetic forces are transmitted by particles like the photon (the carrier of electromagnetic forces). However, the standard model does not predict the existence of any particle—say, χ—that could be the dark matter. Most efforts to go beyond the standard model of particle physics have been based on the idea of supersymmetry, and most versions of supersymmetry predict that there will be a stable weakly interacting massive particle (WIMP) that would be a natural candidate for the χ particles. Dark matter made of WIMPs would be "cold" dark matter (CDM), and a version of CDM theory has become the standard theory of structure formation in cosmology. Its predictions agree very well with the observed properties of the universe on large scales, but there may be disagreements on scales smaller than galaxies. See also: Elementary particle; Standard model; Supersymmetry

Evidence for weakly interacting dark matter

There is now abundant evidence for dark matter around galaxies and clusters of galaxies, and on larger scales in the universe. In the solar system, the more distant a planet is from the Sun, the slower its velocity around the Sun. This is as expected from standard gravity theory and mechanics, since almost all the gravitating mass in the solar system is in the Sun at its center. But gas and satellites at large distances from galaxies have orbital velocities similar to those at smaller distances from the center, which indicates that most of the mass in the galaxy must not be near the center, where most stars are, but in a roughly spherical dark matter halo that extends to perhaps ten times the optical size of the galaxy and has a mass at least ten times that of all the stars. Confirmation of the existence of such dark-matter halos has come from gravitational lensing observations, showing that light from more distant galaxies is bent by the gravity of nearer galaxies. See also: Celestial mechanics; Galaxy, external; Gravitational lens; Milky Way Galaxy

Large, nearly spherical halos are expected to form by gravitational collapse in the expanding universe. Once such a halo forms, the gas in it (mostly hydrogen and helium) can continue to collide and convert kinetic energy to radiation, sinking closer to the center of attraction. If the gas retains its angular momentum, it will spin faster as its radius decreases, and will ultimately form a disk. When much of the gas has formed into stars, such a galaxy would be a spiral, the most abundant type of large galaxy. Collisions between such disk galaxies may produce most elliptical galaxies and bulges of spiral galaxies. But if the dark matter can interact only weakly—that is, via the weak interactions, carried by the gauge particles (generalizations of the photon) W^+, W^-, and Z^0—but not strongly or electromagnetically, that would explain why χ particles cannot lose energy by radiation, but must form extended dark halos. Weakly interacting χ particles would also not be concentrated in minerals on Earth, or anywhere else in the disk of the Milky Way Galaxy for that matter, in agreement with observations. See also: Intermediate vector boson; Weak nuclear interactions

There is also much evidence for dark matter in clusters of galaxies. The astronomer Fritz Zwicky pointed out in 1933 that the galaxies in one nearby cluster were moving at such high speeds that they would not be held together gravitationally unless there was much more mass than was indicated by the light from their stars. This same was subsequently found to be true of other clusters. Later, similar conclusions were reached from x-ray observations and gravitational lensing observations of clusters. See also: X-ray astronomy

Measurements of the typical angular sizes of structures in the cosmic background radiation—the heat radiation of the big bang—provide information about the composition of the universe, and again lead to the conclusion that most of the matter in the universe is dark matter. All of these data indicate that the total amount of dark matter is about 30–40% of the critical density required to close the universe, while the total amount of ordinary matter is only about 4–5% of the critical density, and the amount of visible matter is less than half a percent of the critical density. The density in units of critical density is usually written as Ω, a dimensionless number; the universe will expand forever if the total average density $\Omega < 1$, and will eventually collapse if $\Omega > 1$. Expressed this way, the average, or cosmological, dark-matter density is $\Omega_{dm} \approx 0.3–0.4$, the density of all ordinary matter (baryons) is $\Omega_b \approx 0.04–0.05$, while the density of visible matter is only $\Omega_{vis} \approx 0.005$. See also: Big bang theory; Cosmic background radiation

Nature of dark matter

Since about 1980, when the evidence for dark matter became convincing, there have been various theories proposed concerning its possible composition. That dark matter is invisible suggests that the χ particles are electrically neutral. The leading candidates for the dark-matter particle are axions and supersymmetric WIMPs, since both were predicted on the basis of particle physics theories that were motivated by laboratory experiments, and it was only subsequently appreciated that they could solve the dark-matter mystery.

Supersymmetric WIMPs

Supersymmetry is the hypothesis that there is a relationship between the two known classes of particles, bosons and fermions. The bosons, such as the photon and the graviton, are responsible for the forces of nature. The fermions—including the atomic building blocks, the proton, neutron, and electron—are the matter particles. According to supersymmetry, for every kind of boson in the universe, there must also be a corresponding fermion with the same electric charge and very similar interactions with other particles. For example, the supersymmetric analog of the photon has been named the photino, and like the photon, it would be electrically neutral. Since these hypothetical sypersymmetric partner particles have not been discovered yet, if supersymmetry is right their masses must be too large for them to have been produced at current particle accelerators. Thus far, the evidence for supersymmetry is only indirect, but if the theory is right many supersymmetric partner particles should be produced at accelerators such as the Large Hadron Collider (LHC) being built in Geneva, Switzerland and scheduled to start operating in 2006. See also: Particle accelerator; Photon; Quantum statistics

In most versions of supersymmetry, there is a new conserved quantum number called R-parity, and the ordinary particles all have R-parity equal to +1, while the superpartner particles all have R-parity equal to −1. Thus while heavier superpartner particles can decay into lighter ones (plus ordinary particles), the lightest superpartner (LSP) must be stable, since there is no lighter negative R-parity particle into which it can decay. Thus, the universe should be full of LSP particles if the temperatures in the early universe was high enough to produce supersymmetric partner particles—which is the case according to most theories of the early universe. See also: Conservation laws (physics); Inflationary universe cosmology

This argument was first published in 1982, with the gravitino (the superpartner of the graviton) as the LSP. In currently favored versions of supersymmetry theory, however, the LSP is a neutralino (the superpartner of some other neutral particle) such as the photino; the theory of such dark-matter particles was published in 1984. Neutralinos would be massive but have interactions like those of neutrinos and other particles that interact only via the weak interaction (and gravity); thus they would be supersymmetric WIMPs. These hypothetical particles would mostly go through whole planets without ever interacting. Nevertheless, it is feasible to search for such WIMPs with very sensitive new instruments. See also: Graviton

Searching for WIMPs

Efforts to detect WIMPs directly are based on detecting their scattering from nuclei. The weak nature of the interactions of WIMPs means that the probability of their interacting is very small. But for the few that do interact, the amount of energy delivered in the collision is large enough to detect with sensitive instruments. Since the WIMPs are supposed to be gravitationally bound to the Milky Way Galaxy, their velocities v are approximately 300 km/s (180 mi/s), a thousandth the speed of light, c. It follows that the ratio of their kinetic energy ($= mv^2/2$ for these nonrelativistic particles of mass m) to their rest mass energy (mc^2) will be $½(v/c)^2 \approx 0.5 \times 10^{-6}$. If their rest mass is approximately one hundred times the mass of a proton—the sort of mass expected since the charged superpartners have not yet been produced at particle accelerators—then their kinetic energy will be about 50 kiloelectronvolts. All this kinetic energy would be transferred as recoil energy to an equal-mass nucleus struck head on. This would have two different sorts of effects in a crystal: vibrations and electronic excitations. The vibrations would quickly become random heat vibrations, and these can be detected in crystals cooled to a small fraction of a degree above absolute zero. The excited electrons could be detected as a current if the crystal is a semiconductor, or as emitted light if the crystal is transparent and has the appropriate electronic structure. It is very useful to detect both vibrations and electron excitations, since the main background of events that could be mistaken for WIMP interactions is scattering of electrons in the detector by energetic photons (Compton scattering). Since the background events would put more energy into electron excitations than into crystal lattice vibrations, this can be used to help tell whether a possible signal is coming from WIMP scattering. Many experiments of this type are being built around the world. It is desirable to put these detectors deep underground to shield them from cosmic rays. See also: Compton effect; Cosmic rays; Lattice vibrations; Particle detector; Scintillation counter

WIMPs can also be detected indirectly, for example by looking for particles coming from their annihilation. Supersymmetric WIMPs (neutralinos) are their own antiparticles, and their annihilation products include energetic photons (gamma rays) and neutrinos, as well as particle-antiparticle pairs, such as electrons and positrons, or protons and antiprotons. One possible signal is gamma rays from WIMP annihilation at the center of the Milky Way Galaxy, where the WIMP density is elevated because of the structure of dark-matter halos, and perhaps further elevated (or perhaps alternatively decreased—this is a controversial issue) by the presence of a black hole at the galactic center. The Gamma-ray Large Area Space Telescope (GLAST), scheduled for launch in 2006, will look for this signal with greatly increased sensitivity. Another important signal that has been searched for is neutrinos coming from WIMP annihilation in the center of the Sun or the center of the Earth, where some will settle after being slowed down by scattering off atomic nuclei in the Sun or Earth. See also: Antimatter; Black hole; Gamma-ray astronomy; Neutrino astronomy

WIMPs are also expected to be produced at accelerators such as the LHC from rapid decays of heavier supersymmetric partner particles, and this could be where they are discovered first if they are not seen before that in direct or indirect search experiments. Failure to see supersymmetric particles at LHC energies would mean that current ideas about supersymmetry are wrong.

WIMPs as cold dark matter

The CDM theory was developed to describe how galaxies and clusters of galaxies would form in a universe in which the dark matter is WIMPs or other particles that would have been "cold" in the early universe—that is, moving so sluggishly that their motion can be neglected. "Hot" dark matter (HDM) had earlier been considered. HDM refers to light particles like neutrinos, thought to have rest energies of perhaps a few electronvolts. Such particles would be moving at nearly the speed of light in the hot early universe, and this would inhibit formation of galaxies. The first structures to form in an HDM universe would be objects with the mass of a supercluster of galaxies, and galaxies would have to form subsequently through their fragmentation. But superclusters are still forming today, while most galaxies are old. That HDM predicted the wrong sequence of cosmogony led to its downfall, while CDM is a hierarchical structure formation theory in which smaller things form earlier and merge to form larger and larger structures, up to clusters of galaxies, the largest gravitationally bound objects. See also: Neutrino

The distribution and properties of galaxies predicted by the CDM theory agree beautifully with observations. Only at the centers of galaxies is there a possible discrepancy between theory and observation: theory predicts a density cusp at the center of dark-matter halos, while some observations suggest a more uniform dark-matter density there. Although such a cusp would involve only a tiny fraction of a galaxy's mass, this possible discrepancy is a serious concern for the theory that the dark matter is mostly WIMPs.

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