Matter

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A term that traditionally refers to the substance of which all bodies consist. In Aristotelian physics, each type (species) of material body had a distinct “essential form.” Early modern scientists, however, asserted that there is one universal type of matter. For Isaac Newton, this matter consisted of “solid, massy, hard, impenetrable, movable,” ultimate particles (“atoms”), which were discrete, localized, indivisible bodies. Modern analyses distinguish two types of mass in classical (Newtonian) matter: inertial mass, by which matter retains its state of rest or uniform rectilinear motion in the absence of external forces; and gravitational mass, by which a body exerts forces of attraction on other bodies and by which it reacts to those forces. Expressed in appropriate units, these two properties are numerically equal—a purely experimental fact, unexplained by theory. Albert Einstein made the equality of inertial and gravitational mass a fundamental principle (principle of equivalence), as one of the two postulates of the theory of general relativity. In the equation $E = mc^2$ (where c is the velocity of light), Einstein recognized the equivalence (interconvertibility) of mass (m) and energy (E), which had been distinguished in classical theories. *See also:* GRAVITATION; INERTIA; MASS; RELATIVITY; WEIGHT.

Implications of quantum mechanics

Among the departures from classical thinking instituted by quantum mechanics with regard to matter are the following. Matter in classical mechanics is closely identified with mass; in quantum mechanics, mass is only one among many properties (quantum numbers) that a particle can have, for example, electric charge, spin, and parity. The nearest quantum-mechanical analogs of traditional matter are fermions, having half-integral values of spin. Forces are mediated by exchange of bosons, particles having integral spins (such as photons). Fermions correspond to classical matter in exhibiting impenetrability (a consequence of the exclusion principle), but the correspondence is only rough. For example, fermions can also be exchanged in interactions (a photon and an electron can exchange an electron), and they also exhibit wavelike behavior. States of classical matter-particles were given by their positions and momenta, but in quantum mechanics it is impossible to assign simultaneous precise positions and momenta to particles. Finally, two or more particles in quantum theory can become “entangled,” so that, in the case of two particles that become entangled and separate by a very great distance, an operation on one particle will be immediately responded to by a corresponding change in the other. This “nonlocality” violates traditional notions of what a piece of matter must be, which led Einstein to refer to quantum mechanics as objectionable in implying a “spooky action at a distance.” *See also:* EXCLUSION PRINCIPLE; NONRELATIVISTIC QUANTUM THEORY; QUANTUM ELECTRODYNAMICS; QUANTUM MECHANICS; QUANTUM STATISTICS.

Matter in the universe

Beginning in the 1920s, astronomers accumulated a vast amount of evidence leading to the conclusion that the density of matter in the universe was much larger than that of visible matter. Important steps in this direction were taken in 1933, when Fritz Zwicky found that the amount of visible matter in a number of galaxy clusters was far too small to hold the galaxies in the cluster, and in 1983, when Vera Rubin and colleagues found that the rotation curves of individual spiral galaxies implied that the galaxies must be surrounded by a sphere of unseen matter, ten times the amount in the visible galaxy itself. It began to appear that the visible matter might constitute less than 1%, or at most 3%, of the amount of matter required, in the simplest theories, to equal the critical density at which the geometry of the universe would be Euclidean ("flat"), and at which the expansion rate of the universe would gradually slow down, asymptotically approaching zero. Some scientists accepted the implication that the universe was "open," with a hyperbolic geometry and continued expansion forever at a rate that did not approach zero.

Others proposed that missing matter, undetectable by current techniques, might equal the critical density, and many proposals were made regarding the nature of the missing matter. The motivation for seeking the missing matter became stronger with the proposal of the theory of inflation, which required a critical density. However, visible matter is baryonic, consisting almost entirely by mass of protons and neutrons. With the total density of baryonic matter so low, the missing nonbaryonic dark matter would have to be some kind of exotic particle. Candidates for this status included axions and the lightest (nondecaying) supersymmetric particles, photinos or perhaps winos. None of these, nor many other candidates, have been observed. *See also:* DARK MATTER; SUPERSYMMETRY; WEAKLY INTERACTING MASSIVE PARTICLE (WIMP).

It was long realized that such exotic matter was still not enough for closure (critical density), however, and debates arose regarding the nature of the dark energy that was needed to provide the remainder. One popular proposal was that of quintessence, a negative-pressure energy field, perhaps created by particles that had not been suggested in current hypotheses. However, while quintessence theories have not been entirely ruled out, they have been replaced by a different approach. In 1998, results from studies of distant supernovae indicated strongly that the universe is not merely expanding: the rate of expansion is accelerating. It was found that this acceleration has been going on for approximately 5×10^9 years. The new view thus suggested was that some kind of dark antigravitational energy was at work, a product of the vacuum rather than, as with quintessence views, some unknown form of quasimatter. It thus resembles the cosmological constant that Einstein had proposed as a term in his equations designed to preserve the universe from the possibility that it might expand or contract. He abandoned this term after the discovery of the expansion of the universe. *See also:* ACCELERATING UNIVERSE; COSMOLOGICAL CONSTANT; DARK ENERGY.

In 2003, one of the great achievements of the *Wilkinson Microwave Anisotropy Probe* (*WMAP*) was to pin down the distribution as follows: 4% of the matter in the universe is baryonic, 23% is dark nonbaryonic matter, and 73% is something else, generally known as dark energy. Though slightly different values have been proposed, all are within an estimated 5% error range. The *WMAP* results were bolstered by ones from the Sloan Digital Sky Survey (SSDS), also announced in 2003. Several future investigations, expanding and improving on these results, are in preparation. *See also:* COSMOLOGY; SLOAN DIGITAL SKY SURVEY; UNIVERSE; WILKINSON MICROWAVE ANISOTROPY PROBE.

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Additional Readings

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