= Quark =

A quark (/ ?kw??rk / or / ?kw??rk /) is an elementary particle and a fundamental constituent of matter . Quarks combine to form composite particles called hadrons , the most stable of which are protons and neutrons , the components of atomic nuclei . Due to a phenomenon known as color confinement , quarks are never directly observed or found in isolation ; they can be found only within hadrons , such as baryons (of which protons and neutrons are examples) , and mesons . For this reason , much of what is known about quarks has been drawn from observations of the hadrons themselves .

Quarks have various intrinsic properties , including electric charge , mass , color charge and spin . Quarks are the only elementary particles in the Standard Model of particle physics to experience all four fundamental interactions , also known as fundamental forces (electromagnetism , gravitation , strong interaction , and weak interaction) , as well as the only known particles whose electric charges are not integer multiples of the elementary charge .

There are six types of quarks , known as flavors : up , down , strange , charm , top , and bottom . Up and down quarks have the lowest masses of all quarks . The heavier quarks rapidly change into up and down quarks through a process of particle decay : the transformation from a higher mass state to a lower mass state . Because of this , up and down quarks are generally stable and the most common in the universe , whereas strange , charm , bottom , and top quarks can only be produced in high energy collisions (such as those involving cosmic rays and in particle accelerators) . For every quark flavor there is a corresponding type of antiparticle , known as an antiquark , that differs from the quark only in that some of its properties have equal magnitude but opposite sign .

The quark model was independently proposed by physicists Murray Gell @-@ Mann and George Zweig in 1964 . Quarks were introduced as parts of an ordering scheme for hadrons , and there was little evidence for their physical existence until deep inelastic scattering experiments at the Stanford Linear Accelerator Center in 1968 . Accelerator experiments have provided evidence for all six flavors . The top quark was the last to be discovered at Fermilab in 1995 .

= = Classification = =

The Standard Model is the theoretical framework describing all the currently known elementary particles . This model contains six flavors of quarks (q) , named up (u) , down (d) , strange (s) , charm (c) , bottom (b) , and top (t) . Antiparticles of quarks are called antiquarks , and are denoted by a bar over the symbol for the corresponding quark , such as u for an up antiquark . As with antimatter in general , antiquarks have the same mass , mean lifetime , and spin as their respective quarks , but the electric charge and other charges have the opposite sign .

Quarks are spin @-@ 1 ? 2 particles , implying that they are fermions according to the spin @-@ statistics theorem . They are subject to the Pauli exclusion principle , which states that no two identical fermions can simultaneously occupy the same quantum state . This is in contrast to bosons (particles with integer spin) , any number of which can be in the same state . Unlike leptons , quarks possess color charge , which causes them to engage in the strong interaction . The resulting attraction between different quarks causes the formation of composite particles known as hadrons (see " Strong interaction and color charge " below) .

The quarks which determine the quantum numbers of hadrons are called valence quarks ; apart from these , any hadron may contain an indefinite number of virtual (or sea) quarks , antiquarks , and gluons which do not influence its quantum numbers . There are two families of hadrons : baryons , with three valence quarks , and mesons , with a valence quark and an antiquark . The most common baryons are the proton and the neutron , the building blocks of the atomic nucleus . A great number of hadrons are known (see list of baryons and list of mesons) , most of them differentiated by their quark content and the properties these constituent quarks confer . The existence of " exotic " hadrons with more valence quarks , such as tetraquarks (qqqq) and pentaquarks (qqqqq) , has been conjectured but not proven . However , on 13 July 2015 , the LHCb collaboration at CERN reported results consistent with pentaquark states .

Elementary fermions are grouped into three generations , each comprising two leptons and two quarks . The first generation includes up and down quarks , the second strange and charm quarks , and the third bottom and top quarks . All searches for a fourth generation of quarks and other elementary fermions have failed , and there is strong indirect evidence that no more than three generations exist . Particles in higher generations generally have greater mass and less stability , causing them to decay into lower @-@ generation particles by means of weak interactions . Only first @-@ generation (up and down) quarks occur commonly in nature . Heavier quarks can only be created in high @-@ energy collisions (such as in those involving cosmic rays) , and decay quickly ; however , they are thought to have been present during the first fractions of a second after the Big Bang , when the universe was in an extremely hot and dense phase (the quark epoch) . Studies of heavier quarks are conducted in artificially created conditions , such as in particle accelerators .

Having electric charge , mass , color charge , and flavor , quarks are the only known elementary particles that engage in all four fundamental interactions of contemporary physics : electromagnetism , gravitation , strong interaction , and weak interaction . Gravitation is too weak to be relevant to individual particle interactions except at extremes of energy (Planck energy) and distance scales (Planck distance) . However , since no successful quantum theory of gravity exists , gravitation is not described by the Standard Model .

See the table of properties below for a more complete overview of the six quark flavors ' properties .

= = History = =

The quark model was independently proposed by physicists Murray Gell @-@ Mann (pictured) and George Zweig in 1964 . The proposal came shortly after Gell @-@ Mann 's 1961 formulation of a particle classification system known as the Eightfold Way ? or , in more technical terms , SU (3) flavor symmetry . Physicist Yuval Ne 'eman had independently developed a scheme similar to the Eightfold Way in the same year .

At the time of the quark theory 's inception , the " particle zoo " included , amongst other particles , a multitude of hadrons . Gell @-@ Mann and Zweig posited that they were not elementary particles , but were instead composed of combinations of quarks and antiquarks . Their model involved three flavors of quarks , up , down , and strange , to which they ascribed properties such as spin and electric charge . The initial reaction of the physics community to the proposal was mixed . There was particular contention about whether the quark was a physical entity or a mere abstraction used to explain concepts that were not fully understood at the time .

In less than a year , extensions to the Gell @-@ Mann ? Zweig model were proposed . Sheldon Lee Glashow and James Bjorken predicted the existence of a fourth flavor of quark , which they called charm . The addition was proposed because it allowed for a better description of the weak interaction (the mechanism that allows quarks to decay) , equalized the number of known quarks with the number of known leptons , and implied a mass formula that correctly reproduced the masses of the known mesons .

In 1968 , deep inelastic scattering experiments at the Stanford Linear Accelerator Center (SLAC) showed that the proton contained much smaller , point @-@ like objects and was therefore not an elementary particle . Physicists were reluctant to firmly identify these objects with quarks at the time , instead calling them " partons " ? a term coined by Richard Feynman . The objects that were observed at SLAC would later be identified as up and down quarks as the other flavors were discovered . Nevertheless , " parton " remains in use as a collective term for the constituents of hadrons (quarks , antiquarks , and gluons) .

The strange quark 's existence was indirectly validated by SLAC 's scattering experiments : not only was it a necessary component of Gell @-@ Mann and Zweig 's three @-@ quark model , but it provided an explanation for the kaon (K) and pion (?) hadrons discovered in cosmic rays in 1947 .

In a 1970 paper , Glashow , John Iliopoulos and Luciano Maiani presented the so @-@ called GIM

mechanism to explain the experimental non @-@ observation of flavor @-@ changing neutral currents . This theoretical model required the existence of the as @-@ yet undiscovered charm quark . The number of supposed quark flavors grew to the current six in 1973 , when Makoto Kobayashi and Toshihide Maskawa noted that the experimental observation of CP violation could be explained if there were another pair of quarks .

Charm quarks were produced almost simultaneously by two teams in November 1974 (see November Revolution) ? one at SLAC under Burton Richter , and one at Brookhaven National Laboratory under Samuel Ting . The charm quarks were observed bound with charm antiquarks in mesons . The two parties had assigned the discovered meson two different symbols , J and ? ; thus , it became formally known as the J / ? meson . The discovery finally convinced the physics community of the quark model 's validity .

In the following years a number of suggestions appeared for extending the quark model to six quarks . Of these , the 1975 paper by Haim Harari was the first to coin the terms top and bottom for the additional quarks .

In 1977 , the bottom quark was observed by a team at Fermilab led by Leon Lederman . This was a strong indicator of the top quark 's existence : without the top quark , the bottom quark would have been without a partner . However , it was not until 1995 that the top quark was finally observed , also by the CDF and DØ teams at Fermilab . It had a mass much larger than had been previously expected , almost as large as that of a gold atom .

= = Etymology = =

For some time , Gell @-@ Mann was undecided on an actual spelling for the term he intended to coin , until he found the word quark in James Joyce 's book Finnegans Wake :

Gell @-@ Mann went into further detail regarding the name of the quark in his book The Quark and the Jaguar :

In 1963 , when I assigned the name " quark " to the fundamental constituents of the nucleon , I had the sound first , without the spelling , which could have been " kwork " . Then , in one of my occasional perusals of Finnegans Wake , by James Joyce , I came across the word " quark " in the phrase " Three quarks for Muster Mark " . Since " quark " (meaning , for one thing , the cry of the gull) was clearly intended to rhyme with " Mark " , as well as " bark " and other such words , I had to find an excuse to pronounce it as " kwork " . But the book represents the dream of a publican named Humphrey Chimpden Earwicker . Words in the text are typically drawn from several sources at once , like the " portmanteau " words in Through the Looking @-@ Glass . From time to time , phrases occur in the book that are partially determined by calls for drinks at the bar . I argued , therefore , that perhaps one of the multiple sources of the cry " Three quarks for Muster Mark " might be " Three quarts for Mister Mark " , in which case the pronunciation " kwork " would not be totally unjustified . In any case , the number three fitted perfectly the way quarks occur in nature .

Zweig preferred the name ace for the particle he had theorized , but Gell @-@ Mann 's terminology came to prominence once the quark model had been commonly accepted .

The quark flavors were given their names for several reasons . The up and down quarks are named after the up and down components of isospin , which they carry . Strange quarks were given their name because they were discovered to be components of the strange particles discovered in cosmic rays years before the quark model was proposed ; these particles were deemed " strange " because they had unusually long lifetimes . Glashow , who coproposed charm quark with Bjorken , is quoted as saying , " We called our construct the ' charmed quark ' , for we were fascinated and pleased by the symmetry it brought to the subnuclear world . " The names " bottom " and " top " , coined by Harari , were chosen because they are " logical partners for up and down quarks " . In the past , bottom and top quarks were sometimes referred to as " beauty " and " truth " respectively , but these names have somewhat fallen out of use . While " truth " never did catch on , accelerator complexes devoted to massive production of bottom quarks are sometimes called " beauty factories " .

= = Properties = =

= = = Electric charge = = =

Quarks have fractional electric charge values ? either 1 ? 3 or 2 ? 3 times the elementary charge (e) , depending on flavor . Up , charm , and top quarks (collectively referred to as up @-@ type quarks) have a charge of + 2 ? 3 e , while down , strange , and bottom quarks (down @-@ type quarks) have ? 1 ? 3 e . Antiquarks have the opposite charge to their corresponding quarks ; up @-@ type antiquarks have charges of ? 2 ? 3 e and down @-@ type antiquarks have charges of + 1 ? 3 e . Since the electric charge of a hadron is the sum of the charges of the constituent quarks , all hadrons have integer charges : the combination of three quarks (baryons) , three antiquarks (antibaryons) , or a quark and an antiquark (mesons) always results in integer charges . For example , the hadron constituents of atomic nuclei , neutrons and protons , have charges of 0 e and + 1 e respectively ; the neutron is composed of two down quarks and one up quark , and the proton of two up quarks and one down quark .

= = = Spin = = =

Spin is an intrinsic property of elementary particles , and its direction is an important degree of freedom . It is sometimes visualized as the rotation of an object around its own axis (hence the name " spin ") , though this notion is somewhat misguided at subatomic scales because elementary particles are believed to be point @-@ like .

Spin can be represented by a vector whose length is measured in units of the reduced Planck constant ? (pronounced " h bar ") . For quarks , a measurement of the spin vector component along any axis can only yield the values + ? / 2 or ? ? / 2 ; for this reason quarks are classified as spin @-@ 1 ? 2 particles . The component of spin along a given axis ? by convention the z axis ? is often denoted by an up arrow ? for the value + 1 ? 2 and down arrow ? for the value ? 1 ? 2 , placed after the symbol for flavor . For example , an up quark with a spin of + 1 ? 2 along the z axis is denoted by u ? .

= = = Weak interaction = = =

A quark of one flavor can transform into a quark of another flavor only through the weak interaction , one of the four fundamental interactions in particle physics . By absorbing or emitting a W boson , any up @-@ type quark (up , charm , and top quarks) can change into any down @-@ type quark (down , strange , and bottom quarks) and vice versa . This flavor transformation mechanism causes the radioactive process of beta decay , in which a neutron (n) " splits " into a proton (p) , an electron (e ?) and an electron antineutrino (?
e) (see picture) . This occurs when one of the down quarks in the neutron (udd) decays into an up quark by emitting a virtual W ? boson , transforming the neutron into a proton (uud) . The W ? boson then decays into an electron and an electron antineutrino .

Both beta decay and the inverse process of inverse beta decay are routinely used in medical applications such as positron emission tomography (PET) and in experiments involving neutrino detection .

While the process of flavor transformation is the same for all quarks , each quark has a preference to transform into the quark of its own generation . The relative tendencies of all flavor transformations are described by a mathematical table , called the Cabibbo ? Kobayashi ? Maskawa matrix (CKM matrix) . Enforcing unitarity , the approximate magnitudes of the entries of the CKM matrix are :

<formula>

where Vij represents the tendency of a quark of flavor i to change into a quark of flavor j (or vice versa) .

There exists an equivalent weak interaction matrix for leptons (right side of the W boson on the above beta decay diagram) , called the Pontecorvo ? Maki ? Nakagawa ? Sakata matrix (PMNS matrix) . Together , the CKM and PMNS matrices describe all flavor transformations , but the links between the two are not yet clear .

= = = Strong interaction and color charge = = =

According to quantum chromodynamics (QCD) , quarks possess a property called color charge . There are three types of color charge , arbitrarily labeled blue , green , and red . Each of them is complemented by an anticolor ? antiblue , antigreen , and antired . Every quark carries a color , while every antiquark carries an anticolor .

The system of attraction and repulsion between quarks charged with different combinations of the three colors is called strong interaction , which is mediated by force carrying particles known as gluons ; this is discussed at length below . The theory that describes strong interactions is called quantum chromodynamics (QCD) . A quark , which will have a single color value , can form a bound system with an antiquark carrying the corresponding anticolor . The result of two attracting quarks will be color neutrality : a quark with color charge ? plus an antiquark with color charge ? ? will result in a color charge of 0 (or " white " color) and the formation of a meson . This is analogous to the additive color model in basic optics . Similarly , the combination of three quarks , each with different color charges , or three antiquarks , each with anticolor charges , will result in the same " white " color charge and the formation of a baryon or antibaryon .

In modern particle physics , gauge symmetries ? a kind of symmetry group ? relate interactions between particles (see gauge theories) . Color SU (3) (commonly abbreviated to SU (3) c) is the gauge symmetry that relates the color charge in quarks and is the defining symmetry for quantum chromodynamics . Just as the laws of physics are independent of which directions in space are designated x , y , and z , and remain unchanged if the coordinate axes are rotated to a new orientation , the physics of quantum chromodynamics is independent of which directions in three @-@ dimensional color space are identified as blue , red , and green . SU (3) c color transformations correspond to " rotations " in color space (which , mathematically speaking , is a complex space) . Every quark flavor f , each with subtypes fB , fG , fR corresponding to the quark colors , forms a triplet : a three @-@ component quantum field which transforms under the fundamental representation of SU (3) c . The requirement that SU (3) c should be local ? that is , that its transformations be allowed to vary with space and time ? determines the properties of the strong interaction . In particular , it implies the existence of eight gluon types to act as its force carriers .

= = = Mass = = =

Two terms are used in referring to a quark 's mass : current quark mass refers to the mass of a quark by itself , while constituent quark mass refers to the current quark mass plus the mass of the gluon particle field surrounding the quark . These masses typically have very different values . Most of a hadron 's mass comes from the gluons that bind the constituent quarks together , rather than from the quarks themselves . While gluons are inherently massless , they possess energy ? more specifically , quantum chromodynamics binding energy (QCBE) ? and it is this that contributes so greatly to the overall mass of the hadron (see mass in special relativity) . For example , a proton has a mass of approximately 938 MeV / c2 , of which the rest mass of its three valence quarks only contributes about 9 MeV / c2 ; much of the remainder can be attributed to the field energy of the gluons . See Chiral symmetry breaking .

The Standard Model posits that elementary particles derive their masses from the Higgs mechanism , which is associated to the Higgs boson . It is hoped that further research into the reasons for the top quark 's large mass of ~ 173 GeV / c2 , almost the mass of a gold atom , might reveal more about the origin of the mass of quarks and other elementary particles .

= = = Table of properties = = =

The following table summarizes the key properties of the six quarks . Flavor quantum numbers (isospin (I3) , charm (C) , strangeness (S , not to be confused with spin) , topness (T) , and bottomness (B ?)) are assigned to certain quark flavors , and denote qualities of quark @-@ based systems and hadrons . The baryon number (B) is + 1 ? 3 for all quarks , as baryons are made of three quarks . For antiquarks , the electric charge (Q) and all flavor quantum numbers (B , I3 , C , S , T , and B ?) are of opposite sign . Mass and total angular momentum (J ; equal to spin for point particles) do not change sign for the antiquarks .