= 20 nm , W =
20 nm) CMOS transistors operated at cryogenic temperature over a range of ? 269 ° C (4 K) to about ? 258 ° C (15 K) . The electron wavefunction spreads in a semiconductor lattice and negligibly interacts with the valence band electrons , so it can be treated in the single particle formalism , by replacing its mass with the effective mass tensor .

= = Characteristics = =

= = = Classification = = =

In the Standard Model of particle physics , electrons belong to the group of subatomic particles called leptons , which are believed to be fundamental or elementary particles . Electrons have the lowest mass of any charged lepton (or electrically charged particle of any type) and belong to the first @-@ generation of fundamental particles . The second and third generation contain charged leptons , the muon and the tau , which are identical to the electron in charge , spin and interactions , but are more massive . Leptons differ from the other basic constituent of matter , the quarks , by their lack of strong interaction . All members of the lepton group are fermions , because they all have half @-@ odd integer spin ; the electron has spin 1 / 2 .

= = = Fundamental properties = = =

The invariant mass of an electron is approximately 9 @.@ 109 × 10 ? 31 kilograms , or 5 @.@ 489 × 10 ? 4 atomic mass units . On the basis of Einstein 's principle of mass ? energy equivalence , this mass corresponds to a rest energy of 0 @.@ 511 MeV . The ratio between the mass of a proton and that of an electron is about 1836 . Astronomical measurements show that the proton @-@ to @-@ electron mass ratio has held the same value for at least half the age of the universe , as is predicted by the Standard Model .
Electrons have an electric charge of ? 1 @.@ 602 × 10 ? 19 coulomb , which is used as a standard unit of charge for subatomic particles , and is also called the elementary charge . This elementary charge has a relative standard uncertainty of 2 @.@ 2 × 10 ? 8 . Within the limits of experimental accuracy , the electron charge is identical to the charge of a proton , but with the opposite sign . As the symbol e is used for the elementary charge , the electron is commonly symbolized by e ? , where the minus sign indicates the negative charge . The positron is symbolized by e + because it has the same properties as the electron but with a positive rather than negative charge .
The electron has an intrinsic angular momentum or spin of 1 / 2 . This property is usually stated by referring to the electron as a spin @-@ 1 / 2 particle . For such particles the spin magnitude is ? 3 / 2 ?. while the result of the measurement of a projection of the spin on any axis can only be ± ? / 2 . In addition to spin , the electron has an intrinsic magnetic moment along its spin axis . It is approximately equal to one Bohr magneton , which is a physical constant equal to 9 @.@ 27400915 (23) × 10 ? 24 joules per tesla . The orientation of the spin with respect to the momentum of the electron defines the property of elementary particles known as helicity .
The electron has no known substructure. and it is assumed to be a point particle with a point charge and no spatial extent . In classical physics , the angular momentum and magnetic moment of an object depend upon its physical dimensions . Hence , the concept of a dimensionless electron possessing these properties contrasts to experimental observations in Penning traps which point to finite non @-@ zero radius of the electron . A possible explanation of this paradoxical situation is given below in the " Virtual particles " subsection by taking into consideration the Foldy @-@ Wouthuysen transformation .
The issue of the radius of the electron is a challenging problem of the modern theoretical physics . The admission of the hypothesis of a finite radius of the electron is incompatible to the premises of the theory of relativity . On the other hand , a point @-@ like electron (zero radius) generates serious mathematical difficulties due to the self @-@ energy of the electron tending to infinity .

These aspects have been analyzed in detail by Dmitri Ivanenko and Arseny Sokolov .

Observation of a single electron in a Penning trap shows the upper limit of the particle 's radius is 10 ? 22 meters . Also an upper bound of electron radius of 10 ? 18 meters can be derived using the uncertainty relation in energy .

There is also a physical constant called the " classical electron radius " , with the much larger value of 2 @.@ 8179 × 10 ? 15 m , greater than the radius of the proton . However , the terminology comes from a simplistic calculation that ignores the effects of quantum mechanics ; in reality , the so @-@ called classical electron radius has little to do with the true fundamental structure of the electron .

There are elementary particles that spontaneously decay into less massive particles . An example is the muon , which decays into an electron , a neutrino and an antineutrino , with a mean lifetime of 2 @.@ 2 × 10 ? 6 seconds . However , the electron is thought to be stable on theoretical grounds : the electron is the least massive particle with non @-@ zero electric charge , so its decay would violate charge conservation . The experimental lower bound for the electron 's mean lifetime is 6 @.@ 6 × 1028 years , at a 90 % confidence level .

= = = Quantum properties = = =

As with all particles , electrons can act as waves . This is called the wave ? particle duality and can be demonstrated using the double @-@ slit experiment .

The wave @-@ like nature of the electron allows it to pass through two parallel slits simultaneously , rather than just one slit as would be the case for a classical particle . In quantum mechanics , the wave @-@ like property of one particle can be described mathematically as a complex @-@ valued function , the wave function , commonly denoted by the Greek letter psi (?) . When the absolute value of this function is squared , it gives the probability that a particle will be observed near a location ? a probability density .

Electrons are identical particles because they cannot be distinguished from each other by their intrinsic physical properties . In quantum mechanics , this means that a pair of interacting electrons must be able to swap positions without an observable change to the state of the system . The wave function of fermions , including electrons , is antisymmetric , meaning that it changes sign when two electrons are swapped ; that is , ? (r1 , r2) = ? ? (r2 , r1) , where the variables r1 and r2 correspond to the first and second electrons , respectively . Since the absolute value is not changed by a sign swap , this corresponds to equal probabilities . Bosons , such as the photon , have symmetric wave functions instead .

In the case of antisymmetry , solutions of the wave equation for interacting electrons result in a zero probability that each pair will occupy the same location or state . This is responsible for the Pauli exclusion principle , which precludes any two electrons from occupying the same quantum state . This principle explains many of the properties of electrons . For example , it causes groups of bound electrons to occupy different orbitals in an atom , rather than all overlapping each other in the same orbit .

= = = Virtual particles = = =

In a simplified picture , every photon spends some time as a combination of a virtual electron plus its antiparticle , the virtual positron , which rapidly annihilate each other shortly thereafter . The combination of the energy variation needed to create these particles , and the time during which they exist , fall under the threshold of detectability expressed by the Heisenberg uncertainty relation , ?E · ?t ? ? . In effect , the energy needed to create these virtual particles , ?E , can be " borrowed " from the vacuum for a period of time , ?t , so that their product is no more than the reduced Planck constant , ? ? 6 @.@ 6 × 10 ? 16 eV · s . Thus , for a virtual electron , ?t is at most 1 @.@ 3 × 10 ? 21 s .

While an electron ? positron virtual pair is in existence , the coulomb force from the ambient electric field surrounding an electron causes a created positron to be attracted to the original electron , while

a created electron experiences a repulsion . This causes what is called vacuum polarization . In effect , the vacuum behaves like a medium having a dielectric permittivity more than unity . Thus the effective charge of an electron is actually smaller than its true value , and the charge decreases with increasing distance from the electron . This polarization was confirmed experimentally in 1997 using the Japanese TRISTAN particle accelerator . Virtual particles cause a comparable shielding effect for the mass of the electron .

The interaction with virtual particles also explains the small (about 0 @.@ 1 %) deviation of the intrinsic magnetic moment of the electron from the Bohr magneton (the anomalous magnetic moment) . The extraordinarily precise agreement of this predicted difference with the experimentally determined value is viewed as one of the great achievements of quantum electrodynamics .

The apparent paradox (mentioned above in the properties subsection) of a point particle electron having intrinsic angular momentum and magnetic moment can be explained by the formation of virtual photons in the electric field generated by the electron . These photons cause the electron to shift about in a jittery fashion (known as zitterbewegung) , which results in a net circular motion with precession . This motion produces both the spin and the magnetic moment of the electron . In atoms , this creation of virtual photons explains the Lamb shift observed in spectral lines .

= = = Interaction = = =

An electron generates an electric field that exerts an attractive force on a particle with a positive charge , such as the proton , and a repulsive force on a particle with a negative charge . The strength of this force is determined by Coulomb 's inverse square law . When an electron is in motion , it generates a magnetic field . The Ampère @-@ Maxwell law relates the magnetic field to the mass motion of electrons (the current) with respect to an observer . This property of induction supplies the magnetic field that drives an electric motor . The electromagnetic field of an arbitrary moving charged particle is expressed by the Liénard ? Wiechert potentials , which are valid even when the particle 's speed is close to that of light (relativistic) .

When an electron is moving through a magnetic field , it is subject to the Lorentz force that acts perpendicularly to the plane defined by the magnetic field and the electron velocity . This centripetal force causes the electron to follow a helical trajectory through the field at a radius called the gyroradius . The acceleration from this curving motion induces the electron to radiate energy in the form of synchrotron radiation . The energy emission in turn causes a recoil of the electron , known as the Abraham ? Lorentz ? Dirac Force , which creates a friction that slows the electron . This force is caused by a back @-@ reaction of the electron 's own field upon itself .

Photons mediate electromagnetic interactions between particles in quantum electrodynamics . An isolated electron at a constant velocity cannot emit or absorb a real photon ; doing so would violate conservation of energy and momentum . Instead , virtual photons can transfer momentum between two charged particles . This exchange of virtual photons , for example , generates the Coulomb force . Energy emission can occur when a moving electron is deflected by a charged particle , such as a proton . The acceleration of the electron results in the emission of Bremsstrahlung radiation .

An inelastic collision between a photon (light) and a solitary (free) electron is called Compton scattering . This collision results in a transfer of momentum and energy between the particles , which modifies the wavelength of the photon by an amount called the Compton shift . The maximum magnitude of this wavelength shift is h / mec , which is known as the Compton wavelength . For an electron , it has a value of 2 @.@ 43 × 10 ? 12 m . When the wavelength of the light is long (for instance , the wavelength of the visible light is 0 @.@ 4 ? 0 @.@ 7 ?m) the wavelength shift becomes negligible . Such interaction between the light and free electrons is called Thomson scattering or Linear Thomson scattering .

The relative strength of the electromagnetic interaction between two charged particles , such as an electron and a proton , is given by the fine @-@ structure constant . This value is a dimensionless quantity formed by the ratio of two energies : the electrostatic energy of attraction (or repulsion) at a separation of one Compton wavelength , and the rest energy of the charge . It is given by ? ? 7 @.@ 297353 × 10 ? 3 , which is approximately equal to 1 / 137 .

When electrons and positrons collide , they annihilate each other , giving rise to two or more gamma ray photons . If the electron and positron have negligible momentum , a positronium atom can form before annihilation results in two or three gamma ray photons totalling 1 @.@ 022 MeV . On the other hand , high @-@ energy photons may transform into an electron and a positron by a process called pair production , but only in the presence of a nearby charged particle , such as a nucleus .

In the theory of electroweak interaction , the left @-@ handed component of electron 's wavefunction forms a weak isospin doublet with the electron neutrino . This means that during weak interactions , electron neutrinos behave like electrons . Either member of this doublet can undergo a charged current interaction by emitting or absorbing a W and be converted into the other member . Charge is conserved during this reaction because the W boson also carries a charge , canceling out any net change during the transmutation . Charged current interactions are responsible for the phenomenon of beta decay in a radioactive atom . Both the electron and electron neutrino can undergo a neutral current interaction via a Z0 exchange , and this is responsible for neutrino @-@ electron elastic scattering .

= = = Atoms and molecules = = =

An electron can be bound to the nucleus of an atom by the attractive Coulomb force . A system of one or more electrons bound to a nucleus is called an atom . If the number of electrons is different from the nucleus ' electrical charge , such an atom is called an ion . The wave @-@ like behavior of a bound electron is described by a function called an atomic orbital . Each orbital has its own set of quantum numbers such as energy , angular momentum and projection of angular momentum , and only a discrete set of these orbitals exist around the nucleus . According to the Pauli exclusion principle each orbital can be occupied by up to two electrons , which must differ in their spin quantum number .

Electrons can transfer between different orbitals by the emission or absorption of photons with an energy that matches the difference in potential . Other methods of orbital transfer include collisions with particles , such as electrons , and the Auger effect . To escape the atom , the energy of the electron must be increased above its binding energy to the atom . This occurs , for example , with the photoelectric effect , where an incident photon exceeding the atom 's ionization energy is absorbed by the electron .

The orbital angular momentum of electrons is quantized . Because the electron is charged , it produces an orbital magnetic moment that is proportional to the angular momentum . The net magnetic moment of an atom is equal to the vector sum of orbital and spin magnetic moments of all electrons and the nucleus . The magnetic moment of the nucleus is negligible compared with that of the electrons . The magnetic moments of the electrons that occupy the same orbital (so called , paired electrons) cancel each other out .

The chemical bond between atoms occurs as a result of electromagnetic interactions , as described by the laws of quantum mechanics . The strongest bonds are formed by the sharing or transfer of electrons between atoms , allowing the formation of molecules . Within a molecule , electrons move under the influence of several nuclei , and occupy molecular orbitals ; much as they can occupy atomic orbitals in isolated atoms . A fundamental factor in these molecular structures is the existence of electron pairs . These are electrons with opposed spins , allowing them to occupy the same molecular orbital without violating the Pauli exclusion principle (much like in atoms) . Different molecular orbitals have different spatial distribution of the electron density . For instance , in bonded pairs (i.e. in the pairs that actually bind atoms together) electrons can be found with the maximal probability in a relatively small volume between the nuclei . On the contrary , in non @-@ bonded pairs electrons are distributed in a large volume around nuclei .

= = = Conductivity = = =

If a body has more or fewer electrons than are required to balance the positive charge of the nuclei

, then that object has a net electric charge . When there is an excess of electrons , the object is said to be negatively charged . When there are fewer electrons than the number of protons in nuclei , the object is said to be positively charged . When the number of electrons and the number of protons are equal , their charges cancel each other and the object is said to be electrically neutral . A macroscopic body can develop an electric charge through rubbing , by the triboelectric effect .

Independent electrons moving in vacuum are termed free electrons . Electrons in metals also behave as if they were free . In reality the particles that are commonly termed electrons in metals and other solids are quasi @-@ electrons ? quasiparticles , which have the same electrical charge , spin and magnetic moment as real electrons but may have a different mass . When free electrons ? both in vacuum and metals ? move , they produce a net flow of charge called an electric current , which generates a magnetic field . Likewise a current can be created by a changing magnetic field . These interactions are described mathematically by Maxwell 's equations .

At a given temperature , each material has an electrical conductivity that determines the value of electric current when an electric potential is applied . Examples of good conductors include metals such as copper and gold , whereas glass and Teflon are poor conductors . In any dielectric material , the electrons remain bound to their respective atoms and the material behaves as an insulator . Most semiconductors have a variable level of conductivity that lies between the extremes of conduction and insulation . On the other hand , metals have an electronic band structure containing partially filled electronic bands . The presence of such bands allows electrons in metals to behave as if they were free or delocalized electrons . These electrons are not associated with specific atoms , so when an electric field is applied , they are free to move like a gas (called Fermi gas) through the material much like free electrons .

Because of collisions between electrons and atoms , the drift velocity of electrons in a conductor is on the order of millimeters per second . However , the speed at which a change of current at one point in the material causes changes in currents in other parts of the material , the velocity of propagation , is typically about 75 % of light speed . This occurs because electrical signals propagate as a wave , with the velocity dependent on the dielectric constant of the material .

Metals make relatively good conductors of heat , primarily because the delocalized electrons are free to transport thermal energy between atoms . However , unlike electrical conductivity , the thermal conductivity of a metal is nearly independent of temperature . This is expressed mathematically by the Wiedemann ? Franz law , which states that the ratio of thermal conductivity to the electrical conductivity is proportional to the temperature . The thermal disorder in the metallic lattice increases the electrical resistivity of the material , producing a temperature dependence for electric current .

When cooled below a point called the critical temperature , materials can undergo a phase transition in which they lose all resistivity to electric current , in a process known as superconductivity . In BCS theory , this behavior is modeled by pairs of electrons entering a quantum state known as a Bose ? Einstein condensate . These Cooper pairs have their motion coupled to nearby matter via lattice vibrations called phonons , thereby avoiding the collisions with atoms that normally create electrical resistance . (Cooper pairs have a radius of roughly 100 nm , so they can overlap each other .) However , the mechanism by which higher temperature superconductors operate remains uncertain .

Electrons inside conducting solids , which are quasi @-@ particles themselves , when tightly confined at temperatures close to absolute zero , behave as though they had split into three other quasiparticles : spinons , orbitons and holons . The former carries spin and magnetic moment , the next carries its orbital location while the latter electrical charge .

= = = Motion and energy = = =

According to Einstein 's theory of special relativity , as an electron 's speed approaches the speed of light , from an observer 's point of view its relativistic mass increases , thereby making it more and more difficult to accelerate it from within the observer 's frame of reference . The speed of an electron can approach , but never reach , the speed of light in a vacuum , c . However , when

relativistic electrons ? that is , electrons moving at a speed close to c ? are injected into a dielectric medium such as water , where the local speed of light is significantly less than c , the electrons temporarily travel faster than light in the medium . As they interact with the medium , they generate a faint light called Cherenkov radiation .

The effects of special relativity are based on a quantity known as the Lorentz factor , defined as <formula> where v is the speed of the particle . The kinetic energy Ke of an electron moving with velocity v is :

<formula>

where me is the mass of electron . For example , the Stanford linear accelerator can accelerate an electron to roughly 51 GeV . Since an electron behaves as a wave , at a given velocity it has a characteristic de Broglie wavelength . This is given by ?e = h / p where h is the Planck constant and p is the momentum . For the 51 GeV electron above , the wavelength is about 2 @.@ 4 × 10 ? 17 m , small enough to explore structures well below the size of an atomic nucleus .

= = Formation = =

The Big Bang theory is the most widely accepted scientific theory to explain the early stages in the evolution of the Universe . For the first millisecond of the Big Bang , the temperatures were over 10 billion Kelvin and photons had mean energies over a million electronvolts . These photons were sufficiently energetic that they could react with each other to form pairs of electrons and positrons . Likewise , positron @-@ electron pairs annihilated each other and emitted energetic photons :

? + ? ? e + + e ?

An equilibrium between electrons , positrons and photons was maintained during this phase of the evolution of the Universe . After 15 seconds had passed , however , the temperature of the universe dropped below the threshold where electron @-@ positron formation could occur . Most of the surviving electrons and positrons annihilated each other , releasing gamma radiation that briefly reheated the universe .

For reasons that remain uncertain , during the process of leptogenesis there was an excess in the number of electrons over positrons . Hence , about one electron in every billion survived the annihilation process . This excess matched the excess of protons over antiprotons , in a condition known as baryon asymmetry , resulting in a net charge of zero for the universe . The surviving protons and neutrons began to participate in reactions with each other ? in the process known as nucleosynthesis , forming isotopes of hydrogen and helium , with trace amounts of lithium . This process peaked after about five minutes . Any leftover neutrons underwent negative beta decay with a half @-@ life of about a thousand seconds , releasing a proton and electron in the process ,

n ? p + e ? + ?

e

For about the next 300000 ? 400000 years , the excess electrons remained too energetic to bind with atomic nuclei . What followed is a period known as recombination , when neutral atoms were formed and the expanding universe became transparent to radiation .

Roughly one million years after the big bang , the first generation of stars began to form . Within a star , stellar nucleosynthesis results in the production of positrons from the fusion of atomic nuclei . These antimatter particles immediately annihilate with electrons , releasing gamma rays . The net result is a steady reduction in the number of electrons , and a matching increase in the number of neutrons . However , the process of stellar evolution can result in the synthesis of radioactive isotopes . Selected isotopes can subsequently undergo negative beta decay , emitting an electron and antineutrino from the nucleus . An example is the cobalt @-@ 60 (60Co) isotope , which decays to form nickel @-@ 60 (60Ni) .

At the end of its lifetime , a star with more than about 20 solar masses can undergo gravitational collapse to form a black hole . According to classical physics , these massive stellar objects exert a gravitational attraction that is strong enough to prevent anything , even electromagnetic radiation , from escaping past the Schwarzschild radius . However , quantum mechanical effects are believed to potentially allow the emission of Hawking radiation at this distance . Electrons (and positrons)

are thought to be created at the event horizon of these stellar remnants .

When pairs of virtual particles (such as an electron and positron) are created in the vicinity of the event horizon , the random spatial distribution of these particles may permit one of them to appear on the exterior ; this process is called quantum tunnelling . The gravitational potential of the black hole can then supply the energy that transforms this virtual particle into a real particle , allowing it to radiate away into space . In exchange , the other member of the pair is given negative energy , which results in a net loss of mass @-@ energy by the black hole . The rate of Hawking radiation increases with decreasing mass , eventually causing the black hole to evaporate away until , finally , it explodes .

Cosmic rays are particles traveling through space with high energies . Energy events as high as 3 @.@ 0 × 1020 eV have been recorded . When these particles collide with nucleons in the Earth 's atmosphere , a shower of particles is generated , including pions . More than half of the cosmic radiation observed from the Earth 's surface consists of muons . The particle called a muon is a lepton produced in the upper atmosphere by the decay of a pion .

? ? ? ? ? + ?

?

A muon , in turn , can decay to form an electron or positron .

? ? ? e ? + ?

e + ?

?

= = Observation = =

Remote observation of electrons requires detection of their radiated energy . For example , in high @-@ energy environments such as the corona of a star , free electrons form a plasma that radiates energy due to Bremsstrahlung radiation . Electron gas can undergo plasma oscillation , which is waves caused by synchronized variations in electron density , and these produce energy emissions that can be detected by using radio telescopes .

The frequency of a photon is proportional to its energy . As a bound electron transitions between different energy levels of an atom , it absorbs or emits photons at characteristic frequencies . For instance , when atoms are irradiated by a source with a broad spectrum , distinct absorption lines appear in the spectrum of transmitted radiation . Each element or molecule displays a characteristic set of spectral lines , such as the hydrogen spectral series . Spectroscopic measurements of the strength and width of these lines allow the composition and physical properties of a substance to be determined .

In laboratory conditions , the interactions of individual electrons can be observed by means of particle detectors , which allow measurement of specific properties such as energy , spin and charge . The development of the Paul trap and Penning trap allows charged particles to be contained within a small region for long durations . This enables precise measurements of the particle properties . For example , in one instance a Penning trap was used to contain a single electron for a period of 10 months . The magnetic moment of the electron was measured to a precision of eleven digits , which , in 1980 , was a greater accuracy than for any other physical constant .

The first video images of an electron 's energy distribution were captured by a team at Lund University in Sweden , February 2008 . The scientists used extremely short flashes of light , called attosecond pulses , which allowed an electron 's motion to be observed for the first time .

The distribution of the electrons in solid materials can be visualized by angle @-@ resolved photoemission spectroscopy (ARPES) . This technique employs the photoelectric effect to measure the reciprocal space ? a mathematical representation of periodic structures that is used to infer the original structure . ARPES can be used to determine the direction , speed and scattering of electrons within the material .

= = Plasma applications = =

= = = Particle beams = = =

Electron beams are used in welding . They allow energy densities up to 107 W · cm ? 2 across a narrow focus diameter of 0 @.@ 1 ? 1 @.@ 3 mm and usually require no filler material . This welding technique must be performed in a vacuum to prevent the electrons from interacting with the gas before reaching their target , and it can be used to join conductive materials that would otherwise be considered unsuitable for welding .

Electron @-@ beam lithography (EBL) is a method of etching semiconductors at resolutions smaller than a micrometer . This technique is limited by high costs , slow performance , the need to operate the beam in the vacuum and the tendency of the electrons to scatter in solids . The last problem limits the resolution to about 10 nm . For this reason , EBL is primarily used for the production of small numbers of specialized integrated circuits .

Electron beam processing is used to irradiate materials in order to change their physical properties or sterilize medical and food products . Electron beams fluidise or quasi @-@ melt glasses without significant increase of temperature on intensive irradiation : e.g. intensive electron radiation causes a many orders of magnitude decrease of viscosity and stepwise decrease of its activation energy .

Linear particle accelerators generate electron beams for treatment of superficial tumors in radiation therapy . Electron therapy can treat such skin lesions as basal @-@ cell carcinomas because an electron beam only penetrates to a limited depth before being absorbed , typically up to 5 cm for electron energies in the range 5 ? 20 MeV . An electron beam can be used to supplement the treatment of areas that have been irradiated by X @-@ rays .

Particle accelerators use electric fields to propel electrons and their antiparticles to high energies . These particles emit synchrotron radiation as they pass through magnetic fields . The dependency of the intensity of this radiation upon spin polarizes the electron beam ? a process known as the Sokolov ? Ternov effect . Polarized electron beams can be useful for various experiments . Synchrotron radiation can also cool the electron beams to reduce the momentum spread of the particles . Electron and positron beams are collided upon the particles ' accelerating to the required energies ; particle detectors observe the resulting energy emissions , which particle physics studies .

= = = Imaging = = =

Low @-@ energy electron diffraction (LEED) is a method of bombarding a crystalline material with a collimated beam of electrons and then observing the resulting diffraction patterns to determine the structure of the material . The required energy of the electrons is typically in the range 20 ? 200 eV . The reflection high @-@ energy electron diffraction (RHEED) technique uses the reflection of a beam of electrons fired at various low angles to characterize the surface of crystalline materials . The beam energy is typically in the range 8 ? 20 keV and the angle of incidence is 1 ? 4 ° .

The electron microscope directs a focused beam of electrons at a specimen . Some electrons change their properties , such as movement direction , angle , and relative phase and energy as the beam interacts with the material . Microscopists can record these changes in the electron beam to produce atomically resolved images of the material . In blue light , conventional optical microscopes have a diffraction @-@ limited resolution of about 200 nm . By comparison , electron microscopes are limited by the de Broglie wavelength of the electron . This wavelength , for example , is equal to 0 @.@ 0037 nm for electrons accelerated across a 100 @,@ 000 @-@ volt potential . The Transmission Electron Aberration @-@ Corrected Microscope is capable of sub @-@ 0 @.@ 05 nm resolution , which is more than enough to resolve individual atoms . This capability makes the electron microscope a useful laboratory instrument for high resolution imaging . However , electron microscopes are expensive instruments that are costly to maintain .

Two main types of electron microscopes exist : transmission and scanning . Transmission electron microscopes function like overhead projectors , with a beam of electrons passing through a slice of material then being projected by lenses on a photographic slide or a charge @-@ coupled device .

Scanning electron microscopes rasteri a finely focused electron beam , as in a TV set , across the studied sample to produce the image . Magnifications range from 100 × to 1 @,@ 000 @,@ 000 × or higher for both microscope types . The scanning tunneling microscope uses quantum tunneling of electrons from a sharp metal tip into the studied material and can produce atomically resolved images of its surface .

= = = Other applications = = =

In the free @-@ electron laser (FEL) , a relativistic electron beam passes through a pair of undulators that contain arrays of dipole magnets whose fields point in alternating directions . The electrons emit synchrotron radiation that coherently interacts with the same electrons to strongly amplify the radiation field at the resonance frequency . FEL can emit a coherent high @-@ brilliance electromagnetic radiation with a wide range of frequencies , from microwaves to soft X @-@ rays . These devices may find manufacturing , communication and various medical applications , such as soft tissue surgery .

Electrons are important in cathode ray tubes , which have been extensively used as display devices in laboratory instruments , computer monitors and television sets . In a photomultiplier tube , every photon striking the photocathode initiates an avalanche of electrons that produces a detectable current pulse . Vacuum tubes use the flow of electrons to manipulate electrical signals , and they played a critical role in the development of electronics technology . However , they have been largely supplanted by solid @-@ state devices such as the transistor .