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Excerpt
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1 Introduction

The purpose of this chapter is to provide a brief introduction to the Standard Model of particle physics. In particular, it gives an overview of the fundamental particles and the relationship between these particles and the forces. It also provides an introduction to the interactions of particles in matter and how they are detected and identified in the experiments at modern particle colliders.

1.1 The Standard Model of particle physics

Particle physics is at the heart of our understanding of the laws of nature. It is concerned with the fundamental constituents of the Universe, the *elementary particles*, and the interactions between them, the *forces*. Our current understanding is embodied in the Standard Model of particle physics, which provides a unified picture where the forces between particles are themselves described by the exchange of particles. Remarkably, the Standard Model provides a successful description of all current experimental data and represents one of the triumphs of modern physics.

1.1.1 The fundamental particles

In general, physics aims to provide an effective mathematical description of a physical system, appropriate to the energy scale being considered. The world around us appears to be formed from just a few different particles. Atoms are the bound states of negatively charged electrons (e^-) which orbit around a central nucleus composed of positively charged protons (p) and electrically neutral neutrons (n). The electrons are bound to the nucleus by the electrostatic attraction between opposite charges, which is the low-energy manifestation of the fundamental theory of electromagnetism, namely Quantum Electrodynamics (QED). The rich structure of the properties of the elements of the periodic table emerges from quantum mechanics, which dictates the precise electronic structure of the different atoms. In the atomic nucleus, the protons and neutrons are bound together by the strong nuclear force, which is a manifestation of the fundamental theory of strong interactions,

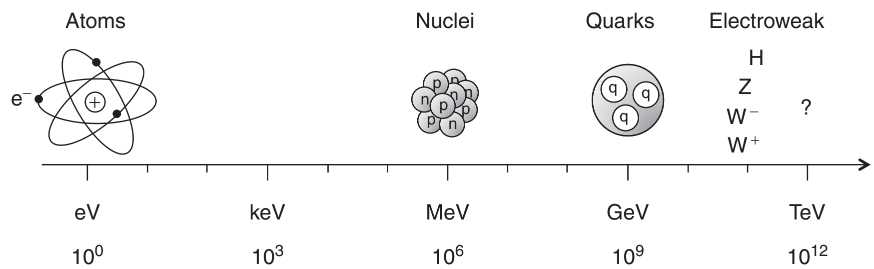

Fig. 1.1 The Universe at different energy scales, from atomic physics to modern particle physics at the TeV scale.

called Quantum Chromodynamics (QCD). The fundamental interactions of particle physics are completed by the weak force, which is responsible for the nuclear β-decays of certain radioactive isotopes and the nuclear fusion processes that fuel the Sun. In both nuclear β-decay and nuclear fusion, another particle, the nearly massless electron neutrino (ν_e) is produced. Almost all commonly encountered physical phenomena can be described in terms of the electron, electron neutrino, proton and neutron, interacting by the electromagnetic, strong and weak forces. The picture is completed by gravity, which although extremely weak, is always attractive and is therefore responsible for large-scale structure in the Universe. This is an appealingly simple physical model with just four "fundamental" particles and four fundamental forces. However, at higher energy scales, further structure is observed, as indicated in Figure 1.1. For example, the protons and neutrons are found to be bound states of (what are believed to be) genuinely fundamental particles called *quarks*, with the proton consisting of two up-quarks and a down-quark, p(uud), and the neutron consisting of two down-quarks and an up-quark, n(ddu).

The electron, the electron neutrino, the up-quark and down-quark are known collectively as the *first generation*. As far as we know, they are elementary particles, rather than being composite, and represent the basic building blocks of the low-energy Universe. However, when particle interactions are studied at the energy scales encountered in high-energy particle colliders, further complexity is revealed. For each of the four first-generation particles, there are exactly two copies which differ only in their masses. These additional eight particles are known as the *second* and *third generations*. For example, the muon (μ^-) is essentially a heavier version of the electron with mass $m_\mu \approx 200\, m_e$, and the third generation tau-lepton (τ^-) is an even heavier copy with $m_\tau \approx 3500\, m_e$. Apart from the differences in masses, which have physical consequences, the properties of the electron, muon and tau-lepton are the same in the sense that they possess exactly the same fundamental interactions.

It is natural to ask whether this pattern is repeated and that there are further generations of particles. Perhaps surprisingly, this seems not to be the case; there is

Table 1.1 The twelve fundamental fermions divided into quarks and leptons. The masses of the quarks are the current masses.

	Leptons				Quarks			
	Particle		Q	mass/GeV	Particle		Q	mass/GeV
First generation	electron	(e^-)	−1	0.0005	down	(d)	−1/3	0.003
	neutrino	(ν_e)	0	$< 10^{-9}$	up	(u)	+2/3	0.005
Second generation	muon	(μ^-)	−1	0.106	strange	(s)	−1/3	0.1
	neutrino	(ν_μ)	0	$< 10^{-9}$	charm	(c)	+2/3	1.3
Third generation	tau	(τ^-)	−1	1.78	bottom	(b)	−1/3	4.5
	neutrino	(ν_τ)	0	$< 10^{-9}$	top	(t)	+2/3	174

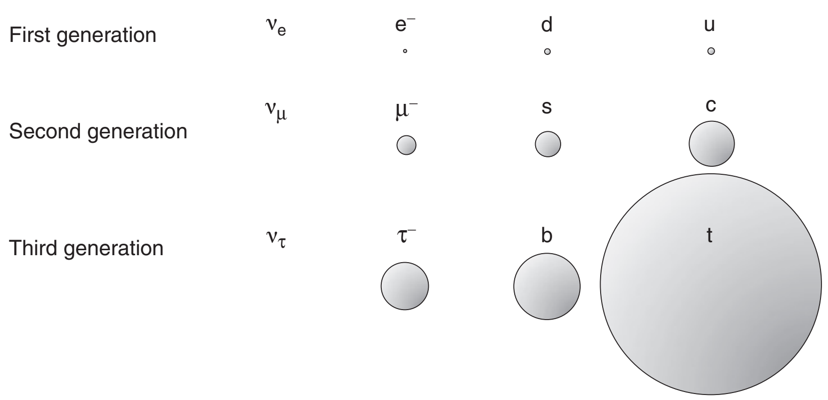

Fig. 1.2 The particles in the three generations of fundamental fermions with the masses indicated by imagined spherical volumes of constant density. In reality, fundamental particles are believed to be point-like.

strong experimental evidence that there are just three generations; hence the matter content of the Universe appears to be in the form of the twelve fundamental spin-half particles listed in Table 1.1. There is a subtlety when it comes to the description of the neutrinos; the ν_e, ν_μ and ν_τ are in fact quantum-mechanical mixtures of the three fundamental neutrino states with well-defined masses, labelled simply ν_1, ν_2 and ν_3. This distinction is only important in the discussion of the behaviour of neutrinos that propagate over large distances, as described in Chapter 13. Whilst it is known that the neutrinos are not massless, the masses are sufficiently small that they have yet to be determined. From the upper limits on the possible neutrino masses, it is clear that they are at least nine orders of magnitude lighter than the other fermions. Apart from the neutrinos, the masses of the particles within a particular generation are found to be rather similar, as illustrated in Figure 1.2. Whilst it is likely that there is some underlying reason for this pattern of masses, it is not currently understood.

Table 1.2 The forces experienced by different particles.

					strong	electromagnetic	weak
Quarks	down-type	d	s	b	✓	✓	✓
	up-type	u	c	t			
Leptons	charged	e^-	μ^-	τ^-		✓	✓
	neutrinos	ν_e	ν_μ	ν_τ			✓

The dynamics of each of the twelve fundamental fermions are described by the Dirac equation of relativistic quantum mechanics, which is the subject of Chapter 4. One important consequence of the Dirac equation is that for each of the twelve fermions there exists an antiparticle state with exactly the same mass, but opposite charge. Antiparticles are denoted either by their charge or by a bar over the corresponding particle symbol. For example, the anti-electron (which is known as the positron) is denoted by e^+, and the anti-up-quark is written $\overline{u}$.

Quarks and leptons

The particles interact with each other through the four fundamental forces, gravity, electromagnetism, the strong force and the weak force. The gravitational force between two individual particles is extremely small and can be neglected in the discussion of particle interactions. The properties of the twelve fundamental fermions are categorised by the types of interaction that they experience, as summarised in Table 1.2. All twelve fundamental particles "feel" the weak force and undergo weak interactions. With the exception of the neutrinos, which are electrically neutral, the other nine particles are electrically charged and participate in the electromagnetic interaction of QED. Only the quarks carry the QCD equivalent of electric charge, called *colour charge*. Consequently, only the quarks feel the strong force. Because of the nature of the QCD interaction, quarks are never observed as free particles, but are always confined to bound states called *hadrons*, such as the proton and neutron. Because the quarks feel the strong force, their properties are very different from those of the electron, muon, tau-lepton and the neutrinos, which are collectively referred to as the *leptons*.

1.1.2 The fundamental forces

In classical electromagnetism, the electrostatic force between charged particles can be described in terms of a scalar potential. This classical description of a force arising from a potential is unsatisfactory on a number of levels. For example, when an electron scatters in the electrostatic potential of a proton, there is a transfer of momentum from one particle to the other without any apparent mediating body.

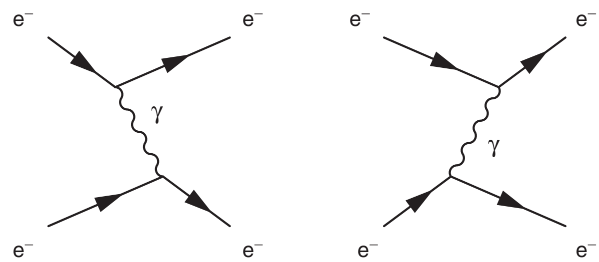

Fig. 1.3 The scattering of two electrons in QED by the exchange of a photon. With time running from left to right, the diagrams indicate the two possible time-orderings.

Regarding this apparent action-at-a-distance, Newton famously wrote "*It is inconceivable that inanimate brute matter should, without the mediation of something else which is not material, operate upon and affect other matter without mutual contact*". Whilst it is convenient to express classical electromagnetism in terms of potentials, it hides the fundamental origin of the electromagnetic interaction.

In modern particle physics, each force is described by a Quantum Field Theory (QFT). In the case of electromagnetism this is the theory of Quantum Electrodynamics (QED), where the interactions between charged particles are mediated by the exchange of *virtual* photons; the meaning of the term virtual is explained in Chapter 5. By describing a force in terms of particle exchange, there is no longer any mysterious action at a distance. As an example, Figure 1.3 shows the interaction between two electrons by the exchange of a photon. In the first diagram, the upper electron emits a photon, which at a later time is absorbed by the lower electron. The effect is to transfer momentum from one electron to the other, and it is this transfer of momentum which manifests itself as a force. The second diagram shows the other possible time-ordering with the lower electron emitting the photon that is subsequently absorbed by the upper electron. Since the exchanged particle is not observed, only the combined effect of these two time-ordered diagrams is physically meaningful.

Each of the three forces of relevance to particle physics is described by a QFT corresponding to the exchange of a spin-1 force-carrying particle, known as a *gauge boson*. The familiar spin-1 photon is the gauge boson of QED. In the case of the strong interaction, the force-carrying particle is called the *gluon* which, like the photon, is massless. The weak charged-current interaction, which is responsible for nuclear β-decay and nuclear fusion, is mediated by the charged W^+ and W^- bosons, which are approximately eighty times more massive than the proton. There is also a weak neutral-current interaction, closely related to the charged current, which is mediated by the electrically neutral Z boson. The relative strengths of the forces associated with the different gauge bosons are indicated in Table 1.3. It should be noted that these numbers are only indicative as the strengths of the forces depend on the distance and energy scale being considered.

Table 1.3 The four known forces of nature. The relative strengths are approximate indicative values for two fundamental particles at a distance of 1 fm $= 10^{-15}$ m (roughly the radius of a proton).

Force	Strength	Boson		Spin	Mass/GeV
Strong	1	Gluon	g	1	0
Electromagnetism	10^{-3}	Photon	γ	1	0
Weak	10^{-8}	W boson	$W^{\pm}$	1	80.4
		Z boson	Z	1	91.2
Gravity	10^{-37}	Graviton?	G	2	0

1.1.3 The Higgs boson

The final element of the Standard Model is the Higgs boson, which was discovered by the ATLAS and CMS experiments at the Large Hadron Collider (LHC) in 2012. The Higgs boson, which has a mass

$$m_{\mathrm{H}} \approx 125\,\mathrm{GeV},$$

differs from all other Standard Model particles. Unlike, the fundamental fermions and the gauge bosons, which are respectively spin-half and spin-1 particles, the Higgs boson is spin-0 scalar particle. As conceived in the Standard Model, the Higgs boson is the only fundamental scalar discovered to date.

The Higgs boson plays a special rôle in the Standard Model; it provides the mechanism by which all other particles acquire mass. Without it the Universe would be a very different, all the particles would be massless and would propagate at the speed of light! In QFT, the Higgs boson can be thought of as an excitation of the Higgs field. Unlike the fields associated with the fundamental fermions and bosons, which have zero expectation values in the vacuum, the Higgs field is believed to have a non-zero vacuum expectation value. It is the interaction of the initially massless particles with this non-zero Higgs field that gives them their masses. The discovery of a Higgs-like particle at the LHC represented a remarkable validation of the theoretical ideas which constitute the Standard Model. The mathematical details of the Higgs mechanism, which are subtle, are discussed in detail in Chapter 17. The masses of the $W^{\pm}$, Z and H bosons are all of the order of 100 GeV, which is known as the electroweak scale. This doesn't happen by chance; in the Standard Model, the masses of the weak gauge bosons are intimately connected to the Higgs mechanism.

1.1.4 The Standard Model vertices

The nature of the strong, electromagnetic and weak forces are determined by the properties of the bosons of the associated quantum field theory, and the way in

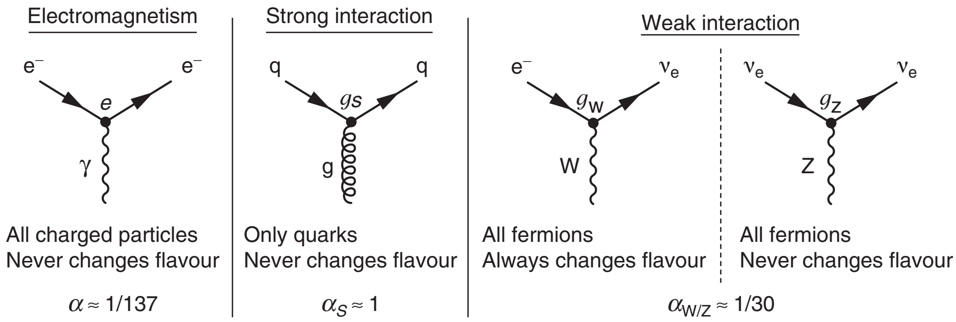

Fig. 1.4 The Standard Model interaction vertices.

which the gauge bosons couple to the spin-half fermions. The coupling of the gauge bosons to the fermions is described by the Standard Model interaction vertices, shown in Figure 1.4. In each case, the interaction is a three-point vertex of the gauge boson and an incoming and outgoing fermion. For each type of interaction there is an associated coupling strength g. For QED the coupling strength is simply the electron charge, $g_{\mathrm{QED}} = e \equiv +|e|$.

A particle couples to a force-carrying boson only if it carries the charge of the interaction. For example, only electrically charged particles couple to the photon. Only the quarks carry the colour charge of QCD, and hence only quarks participate in the strong interaction. All twelve fundamental fermions carry the charge of the weak interaction, known as weak isospin, and therefore they all participate in the weak interaction. The weak charged-current interaction does not correspond to the usual concept of a force as it couples together different flavour fermions. Since the W^+ and W^- bosons have charges of $+e$ and $-e$ respectively, in order to conserve electric charge, the weak charged-current interaction only couples together pairs of fundamental fermions that differ by one unit of electric charge. In the case of the leptons, by definition, the weak interaction couples a charged lepton with its corresponding neutrino,

$$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}, \begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}, \begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}.$$

For the quarks, the weak interaction couples together all possible combinations differing by one unit of charge,

$$\begin{pmatrix}\mathrm{u}\\ \mathrm{d}\end{pmatrix}, \begin{pmatrix}\mathrm{u}\\ \mathrm{s}\end{pmatrix}, \begin{pmatrix}\mathrm{u}\\ \mathrm{b}\end{pmatrix}, \begin{pmatrix}\mathrm{c}\\ \mathrm{d}\end{pmatrix}, \begin{pmatrix}\mathrm{c}\\ \mathrm{s}\end{pmatrix}, \begin{pmatrix}\mathrm{c}\\ \mathrm{b}\end{pmatrix}, \begin{pmatrix}\mathrm{t}\\ \mathrm{d}\end{pmatrix}, \begin{pmatrix}\mathrm{t}\\ \mathrm{s}\end{pmatrix}, \begin{pmatrix}\mathrm{t}\\ \mathrm{b}\end{pmatrix}.$$

The strength of the weak charged-current coupling between the charge $+\frac{2}{3}$ up-type quarks (u, c, t) and the charge $-\frac{1}{3}$ down-type quarks (d, s, b) is greatest for quarks of the same generation. Since the weak interaction is the only known force

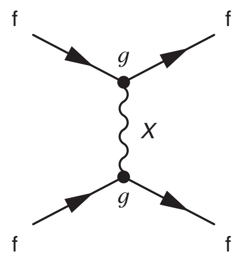

Fig. 1.5 The scattering of two fermions, denoted f, by the exchange of the boson, X. The strength of the fundamental interaction at each of the two three-point ff$X$ vertices is denoted by the coupling constant g.

for which the incoming and outgoing fermions are different, the weak charged-current interaction is particularly important when considering particle decays as it introduces a change of flavour.

The strength of the fundamental interaction between the gauge boson and a fermion is determined by the coupling constant g, which can be thought of as a measure of the probability of a spin-half fermion emitting or absorbing the boson of the interaction. Put more precisely, the quantum-mechanical transition matrix element for an interaction process includes a factor of the coupling constant g for each interaction vertex. For example, the matrix element for the scattering process indicated by Figure 1.5 contains two factors of g, one at each vertex, and therefore

$$\mathcal{M} \propto g^2.$$

Hence, the interaction probability, which is proportional to the matrix element squared, $|\mathcal{M}|^2 = \mathcal{M}\mathcal{M}^*$, contains a factor g^2 from *each* interaction vertex, thus in this example

$$|\mathcal{M}|^2 \propto g^4.$$

Rather than working with the coupling constant itself, it is often more convenient to use the associated dimensionless constant, $\alpha \propto g^2$. In the case of electromagnetism this is the familiar fine-structure constant

$$\alpha = \frac{e^2}{4\pi\varepsilon_0 \hbar c}.$$

One advantage of writing the coupling strength in terms of a dimensionless constant is that the numerical value is independent of the system of units used for a calculation. In addition, the quantum-mechanical probability of the interaction includes a single factor of α for each interaction vertex. The intrinsic strength of the electromagnetic interaction is given by the size of fine-structure constant $\alpha = 1/137$. The QCD interaction is intrinsically stronger with $\alpha_S \sim 1$. The *intrinsic* strength of the weak interaction, with $\alpha_W \sim 1/30$, is in fact greater than that

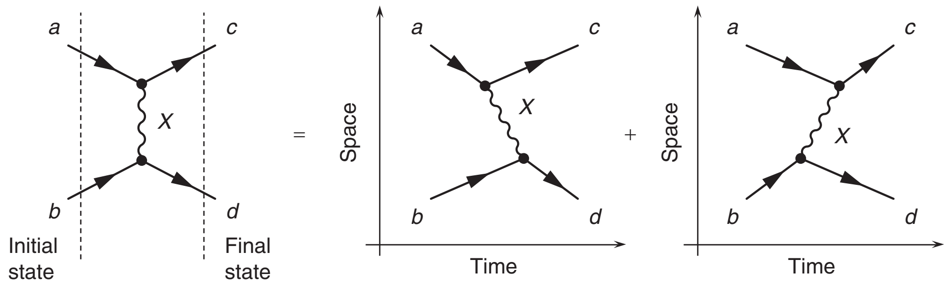

Fig. 1.6 The Feynman diagram for the scattering process $a + b \rightarrow c + d$ and the two time-ordered processes that it represents.

of QED. However, the large mass of the associated W boson means that at relatively low-energy scales, such as those encountered in particle decays, the weak interaction is (as its name suggests) very much weaker than QED.

1.1.5 Feynman diagrams

Feynman diagrams are an essential part of the language of particle physics. They are a powerful representation of transitions between states in quantum field theory and represent all possible time-orderings in which a process can occur. For example, the generic Feynman diagram for the process $a + b \rightarrow c + d$, involving the exchange of boson X, shown in Figure 1.6, represents the sum of the quantum mechanical amplitudes for the two possible time-orderings. It should be remembered that in a Feynman diagram time runs from left to right but only in the sense that the left-hand side of a Feynman diagram represents the initial state, in this case particles a and b, and the right-hand side represents the final state, here c and d. The central part of the Feynman diagram shows the particles exchanged and the Standard Model vertices involved in the interaction, but not the order in which these processes occurred. Feynman diagrams are much more than a pictorial representation of the fundamental physics underlying a particular process. From Quantum Field Theory it is possible to derive simple Feynman rules associated with the vertices and virtual particles in a Feynman diagram. Once the Feynman diagram has been drawn, it is straightforward to write down the quantum-mechanical transition matrix element using the relevant Feynman rules, thus avoiding the need to calculate each process from first principles in Quantum Field Theory.

In general, for each process considered, there will be an infinite number of Feynman diagrams that can be drawn. For example, Figure 1.7 shows Feynman diagrams for the scattering of two electrons by the exchange of either one or two photons. Both diagrams have the same initial and final state, and therefore correspond to the same physical process, $e^-e^- \rightarrow e^-e^-$. Each interaction vertex is associated with a factor e in the matrix element, or equivalently a factor of α in the matrix

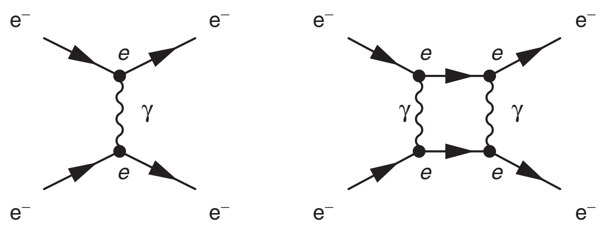

Fig. 1.7 Two Feynman diagrams for $e^-e^- \to e^-e^-$ scattering.

element squared. Thus, the matrix element squared for the diagram involving a single photon exchange and two vertices is proportional to α^2, and that involving two photons and four vertices is proportional to α^4,

$$|\mathcal{M}_\gamma^2| \propto \alpha^2 \quad \text{and} \quad |\mathcal{M}_{\gamma\gamma}^2| \propto \alpha^4.$$

Because the coupling strength of the electromagnetic interaction is relatively small, $\alpha \sim 1/137$, the diagram with four vertices is suppressed by a factor $\mathcal{O}(10^4)$ relative to the diagram with two vertices. In the language of perturbation theory, only the lowest-order term is significant. Consequently, for almost all processes that will be encountered in this book, only the simplest (i.e. lowest-order) Feynman diagram needs to be considered.

For reasons that will become clear in Chapter 4, antiparticles are drawn in Feynman diagrams with arrows pointing in the "backwards in time" direction. In the Standard Model, particles and antiparticles can be created or annihilated only in pairs. This means that the arrows on the incoming and outgoing fermion lines in Standard Model vertices are always in the same sense and flow through the vertex; they never both point towards or away from the vertex.

1.1.6 Particle decays

Most particles decay with a very short lifetime. Consequently, only the relatively few stable and long-lived types of particle are detected in particle physics experiments. There are twelve fundamental spin-half particles (and the twelve corresponding antiparticles), but they are not all stable. For a particle to decay there must be a final state with lower total rest mass that can be reached by a process with a Feynman diagram constructed from the Standard Model vertices. Decays of the fundamental particles all involve the weak charged current which has the only interaction vertex that allows for a change in flavour. For example, since $m_\mu > m_e$ and the neutrinos are almost massless, the muon can decay via $\mu^- \to e^-\overline{\nu}_e\nu_\mu$ through the weak charged-current process with the Feynman diagram of Figure 1.8. Similar diagrams can be drawn for the tau-lepton. Since the electron is the lightest charged lepton, there is no corresponding weak decay process which conserves energy and momentum and consequently the electron is stable.