ELECTRON AS A FUNDAMENTAL PARTICLE

Lakshman Singh
Department of Physics, Gandhi Smarak P.G. College, Samodhpur, Jaunpur.

Abstract

Particle physics allows us to know which the constituent of matter and their interaction are. According to **Standard Model** with success, three of the four fundamental interactions, the strong interaction, the weak interaction and electromagnetic interaction. Fundamental particle is a sub-atomic particle with no sub-structures. Thus not composed of other particles. In the physical sciences, sub-atomic particles are particle much smaller than atom. We review the status of electron as a fundamental particle. We also highlight the essentials of Dirac Equation for electron, Quantum Electrodynamics and present day elementary particle physics where electron as fundamental particle plays a major role. Recent ideas on preon model, string theory as well as leptoquarks questioning the fundamental nature of electron are also discussed.

Introduction

On April 30, 1897, the electron was born as the first official elementary particle. Therefore, history of particle physics begins with the electron. Elementary particle physics deals with the fundamental constituents of matter. The twelve elementary particles of matter and six quarks (up, charm, top, down, strange, bottom) three electrons (electron, muon, tau) and three neutrinos (e, muon are best described in terms of fundamental particles.

In this brief review, we discuss the status of the electron as the fundamental particle. Specifically, we will discuss:

- its status in the standard model of elementary particle physics
- a brief introduction to the Preon model which questions the fundamental nature of electron
- experimental limit of the substructure of electron from Quantum Electrodynamics
- recent experimental limit of leptoquarks
- status of electron in string theory

- possibility of detecting its substructure in future

Electron in Relativistic Quantum Mechanics and Quantum Electrodynamics:

During 1928-30, Dirac proposed the equation of motion for the elementary electron:

$$(\gamma\mu.\partial\mu + m)\psi = 0 \qquad \text{.........................} \; (1)$$

which according to its originator "explains most physics and all chemistry". It successfully predicted antiparticle later discovered as positron in 1933 by C.D. Anderson. It also could successfully explain the degeneracy problem of Hydrogen atom energy level. Later it was the basis for future development of technique of Feynman diagrams as well as Quantum Electrodynamics (QED)[2]. Amongst many of its successes, one of the notable results was the explanation of Lamb shift, the small energy difference of 1058 MHz between 2S½ and 2P½ states of hydrogen. Successes of relativistic quantum mechanics and quantum electrodynamics emphasize the role of electron as fundamental particle.

Experimental limit on the sub-structure of electron from QED:

In this section, we review the experimental data which could show evidence for electron substructure. The equivalent size (L) of the electron in cm is related to the effective mass scale Λ of the substructure by[3]

$$\mathrm{L}(\mathrm{in}10^{-16}\,cm) = (0.1\Lambda(inTeV))^{-1} \qquad \text{...........................} \; (2)$$

Magnetic Moment

According to Dirac, the magnetic moment μ_D of a point like spin ½ particles of mass m is given by

$$\mu_{\mathrm{D}} = \frac{e\hbar}{mc} \qquad \text{.............................} \; (3)$$

or expressing it as $\frac{c}{2}$ times the relevant magneton $\frac{e\hbar}{mc}$,

$$g = 2 \qquad \text{.............................} \; (4)$$

Correction to this arise from the virtual emission and reabsorption of virtual photons. This can be calculated from QED. These processes give the electron an effective size, which is responsible for the modification to the point like value of g. Note that such modification does not signal substructure of the electron. Any substructure would show up as additional corrections to g.

As an illustration, g value of atoms age of the order of 10^5 larger than an atomic magneton. This is thus evidence for substructure and is explained by the magnetic moment being due to atomic electrons. Similarly, proton's magnetic moment is ~2.79 nuclear magneton, while neutron's magnetic moment is -1.91 nuclear magneton, explained in terms of three quark structure of nucleon.

It this appears that if electron has a composite structure, this could manifest itself as a significant deviation of g from the point like values (corrected for QED and strong interactions). This deviation is defined as

$$a = \left(\frac{g-2}{2}\right) \qquad \text{........................ (5)}$$

Experimentally[4]

$$a_{e^-} = (1159652200 \pm 40) \times 10^{-12} \qquad \text{......................... (6)}$$

to be compared with theoretical value[5,6]

$$a_{theory} = (1159652460 \pm 127 \pm 75) \times 10^{-12} \qquad \text{........................ (7)}$$

where the first error comes from the quoted uncertainty in the value of α and the second comes from calculational inaccuracy. The evaluation includes 8^{th} order QED effects which involves calculation of 891 Feynman integrals; hadronic and weak effects are also allowed, but make only a small contribution to a($\sim 10^{-12}$).

With quoted error, the limit of possible substructure of electron is

$$\delta a_e < 0.5 \times 10^{-9} \qquad \text{.......................... (8)}$$

The magnitude of the correction to g^{-2} is model dependent, i.e. whether the composites are bosons or fermions. With fermionic constituents obeying chiral symmetry[3] the correction to g^{-2} is $o\left(\frac{m}{\Lambda}\right)^2$; otherwise it is $o\left(\frac{m}{\Lambda}\right)$ where m is mass of the composite system.

If $(g-2)_e \ is \ o\left(\frac{m}{\Lambda}\right)$,

$$\Lambda > 10^3 TeV \qquad \text{.......................... (9)}$$

If $(g-2)_e \ is \ o\left(\frac{m}{\Lambda}\right)^2$

$$\Lambda > 0.02\, TeV \qquad \text{.......................... (10)}$$

These limits correspond to electron dimension

$$L < 10^{-19} \text{ cm} \qquad \text{.......................... (11)}$$

and

$$L < 2.5\ 10^{-14} \text{cm} \qquad \text{.......................... (12)}$$

respectively.

Electron in the Standard Model of Particle Physics

Electron is the member of the first generation of leptons. According to the standard model, there are six spin ½ leptons and six spin ½ quarks besides spin 1 photon, W and Z bosons and gluons. The quarks and leptons are kept in three generations

Leptons	Quarks		
e	u	:	First generation
υe	d	:	
µ	c	:	Second generation
µ	s	:	

τ	t	:	Third generation
ν_τ	b	:	

Preons

However there are various theoretical motives to get a wider theory than the standard model of particle physics. As noted earlier, according to the present experimental data both leptons (including electron) and quarks are elementary. But then, why there are higher generations of quarks and leptons? Natural explanation is that they correspond to the excited states of the first generation and our experience suggests that such excited states must be composite.

Indeed several models have been suggested in which quarks and leptons are regarded as being made of more fundamental particles. I will not discuss them in details but merely give representative samples.

As early as 1965, Sichichi and Masam[7] suggested that leptons could possess substructure. Their reasoning was simply that just as hadrons are made of hadronic quarks, so leptons may be made off leptonic quarks. In their subsequent search for quarks[8] they quoted limits on these two particular type of quarks. Later Greenberg and Nelson[9] proposed such model. They assumed that leptons are built out of three "leptoquarks" which could have either fractional or integral charges. Later Pati and Salam[10] has also suggested that leoptons must be built out of fractionally charged objectives. Their motivation was to unify leptons with quarks. They first suggested that[10] the four then known leptons (e, ν_e, μ, ν_μ) were a fourth colour variant of the four known quark flavours (u, d, s, c). These would unify the strong with the electromagnetic interactions and would allow proton to decay. Later they suggested[10] that both quarks and leptons could be built out of preons. In one of their versions[10] leptons and quarks are (QC) composites where

Q = A fermion carrying one of the four flavours (u, d, s, c)

C = A colour quarter boson corresponding to three quark classes plus fourth colour for the leptons

δ = Extra neutral singlet boson.

In another version[10] they involved Q and C only.

One of the earlier economic models of preons was that of Harari[11] and Shupe[12]. Specifically, Harari model assumes that both quarks and leptons are constructed of just two types of ultimate particles which Harari calls Rishons (Rishon in Hebre ≡ first of primary). Tow Rishons are designated as T (Tohu ≡ formless in Hebrew) and V (Vohu ≡ void in Hebrew).

The electric charge of T is $+\frac{1}{3}$ while that of V is 0. The electric charges of antiparticles $\bar{T}$ and $\bar{V}$ are $-\frac{1}{3}$ and 0 respectively. In this model,

electron = $\bar{T}\ \bar{T}\ \bar{T}$

positron = T T T

nuutrino = V V V

anti-neutrino = $\bar{V}\ \bar{V}\ \bar{V}$

u- quark = T T V

d- quark = T V V

$\bar{u}$ -quark = $\bar{T}\ \bar{T}\ \bar{V}$

$\bar{d}$ -dark = $\bar{V}\ \bar{V}\ \bar{T}$

which comprise total eight quarks and leptons of the first generation.

One important question arises in such model is why leptons like electrons are colourless and quarks coloured? They argue that three possible ordering of Rishons with u or d quarks are assumed to give rise to the three colours of the quarks

$T_1T_2T_3 \equiv$ Red

$T_1V_2T_3 \equiv$ Blue

$V_1T_2T_3 \equiv$ Green

For leptons, there are no such order of permutations since they are composed of identical Rishons.

However such simplistic model as limitations.

- It cannot explain the occurrence of higher generation of quarks and leptons.
- It cannot provide a satisfactory explanation for the masses within the first generation.

Binding Mechanism of Preons

The mechanism that binds the proposed preons within electron or quark include almost all known interactions: gravity, electromagnetism and quantum chromodynamics. There is also new interaction specific to composite models – hypercolour or technicolour[13]. Of course, in general, technicolour is reserved for Higgs bound states. In analogy with the colour force between quarks mediated by gluons, hypercolour binds preons via hypergluon exchange. The hypercolour interaction is assumed to be confining so that preons whould not be detected as free particles.

In quantum chromodynamics (QCD), colour grop is $SU(3)_c$. The corresponding group for hypercolour is taken as $SU(n)_H$ where n = 2,[14] 3,[14] 4,[16], 5[17], 7[18], 9,[19] or even larger.[17] Other possible hypercolour gluons are also considered in the literature.[20]

Hypercolour model in general predicts that a lepton like electron will exhibit strong interactions at energies high enough (~Λ) such that their substructure is probed. There was suggestion by Pati, Salam and Strathdee[20] that preons carry two new types of charge which are analogous to (but not identical with) electric and magnetic charges. Composite fermion like electron is neutral in both these charges.

The Harari-Shupe Rishon Model[11,12] got its resurrection in the Harari-Seiberg version[15]. In this model, T and V are assigned colour 3 and $\bar{3}$ (nicknamed Colour T Model). Furthermore it is also assumed that Rishons also carry hypercolour.

Prediction of Preon Models and Experimental Tests

1. Proton Decay : If quarks and leptons are composed of the same constituents, their rearragement processes can lead to quark-lepton conversion and hence proton decay. There is not yet confirmation of this prediction.
2. Another strong indication could be to obtain evidence for electron form factors in $e^+ e^- \rightarrow q\,\bar{q}$, $e^+ e^- \rightarrow e^+ e^-$ or $e^+ e^- \rightarrow \mu^+ \mu^-$
3. If both the leptons and the quarks are composite particles that share constituents, an effective contact interaction arise between them.[21] This interaction results in an enhancement of the dilepton differential cross-section at high invariant mass. Based on the absence of high mass dilepton events, limits on the scale of such an effective contact interaction have been set22

$$\Lambda_H > 1.7 - 2.2 \text{ TeV}, \qquad \text{.....................} (13)$$

equivalently

$$L < (2.27 - 2.94) \times 10^{-16}\text{cm} \qquad \text{......................} (14)$$

Coloured Electrons:

The familiar electron carries lepton numbers while the quarks carry colours. But in many theories that extend the standard model, exotic particles called leptoquarks (LQ) also exists. LQ carries both lepton number and colour. The absence of flavour-changing neutral currents constraints leptoquarks to decay within the same generation i.e. a first generation LQ would decay to an electron or electron neutrino or either an up or down quark.

Recent experiments at DESY's HERA electron-proton collider published their backward scattered positron events earlier this year.[23,24] The effect could be due to a leptoquark of mass 200 GeV decaying into a positron and a quark

$$LQ \rightarrow e^{+} + q$$

As early as 1973, Pati and Salam[10] proposed lepton as the fourth colour. Although recent alaysis[25] suggested the events to be only statistical fluctuations, it is the first hint that electron with colour might exist in nature.[26]

Electron in the Light of String Theory

The string theory in particle physics has its root in sixties. Of course, in those days, it was basically a string model for hadrons. It emerged in 1968 when Veneziano27 found a solution to equation which has been developed those days based on Bootstrap model. Nambu28 and several other theorists realised that Veneziano's solution represent in quantum language, the excitations of a string. In order to remove theoretical problems like infinites and tachyons, it was necessary to assume that space-time has larger dimension-26 in the simplest version. If Fermi-Bose symmetry called supersymmetry[29] is invoked, the dimension can be reduced to 10.

According to this theory, the string has vibrational modes and each of these modes represents a particle in spectrum. It implies infinite number of particles-a finite number of massless particles and infinite number of massive particles.

Fundamental scale of the string theory of those days is given by the string tension

$$T = \frac{1}{2\pi\alpha}$$

where α´ is the slope of the "Regge Trajectories".

While hadron phenomenology gives[3,30] with $\alpha' \sim 1 GeV^{-2}$

$$T \sim 0.183\ GeV^2$$

In the subsequent evolution of quantum chromodynamics, the model emerges as a coloured flux tube model of hadrons.[31]

Till then, this has nothing to do with electron. It predicted a massless spin 2 particle but could not explain its physical existence. There is no massless spin 2 hadron. In1974, Schwarz and scherk[32] suggested that this massless particle be the graviton and the theory can be interpreted as a theory of graviton instead of a theory of hadrons. In 1984 Green and Schwarz[33] suggested inclusion of supersymmetry[29] and superstring theory was born.

The method of reducing 26 and 10 dimensions to physically sensible 4 dimensions is however found to be Monique and hence has little predictive value. But the concept is appealing.

As both relativistic quantum mechanics and gravity play important roles in such a theory, the relevant scales of lengths are Planck Energy and Plack Length. The relevant parameters are gravitational constant (G), Planck's constant ($\bar{h}$) and velocity of light (c). The length and energy out of this constants are:

Planck Length $L \sim \left(\frac{G\hbar}{c^3}\right)^{\frac{1}{2}}$ .... (15)

Planck Time $\tau \sim \frac{L}{c}$ .... (16)

Planck Mass $E \sim \frac{\hbar c}{L}$ .... (17)

Putting the values of

$G \approx 6.67 \quad .10^{-8}$ $cm^3\, g^{-1}\, sec^2$ .... (18)

$\hbar \approx 6.58 \quad .10^{-22}$ MeV sec .... (19)

$c \approx 3 \quad .10^{10}$ $cm\, sec^{-1}$ .... (20)

one gets

$L \sim 10^{-33}$ cm .... (21)

$T \sim 10^{-43}$ sec, ... (22)

$E \sim 10^{19}$ GeV .... (23)

In this picture, at least at Planck energy, the electron is a low mode of a vibrating string of dimension ~ 10^{-33} cm. Electron scattering should then be viewed through string diagrams. The string tension of the string will be

$T \sim \frac{1}{2\pi}.10^{38} \quad GeV^2$ .... (24)

with

$\alpha' \sim 10^{-38}\ GeV^2$ .... (25)

instead of mere $T \leq GeV^2$ needed for string model of hadrons.[34]

A generic amplitude for string scattering looks like

T (s, t, u) ≈ [Point like Field Theory]

$$\frac{\Gamma\left(1-\frac{s}{8\pi T}\right)\Gamma\left(1-\frac{t}{8\pi T}\right)\Gamma\left(1-\frac{u}{8\pi T}\right)}{\Gamma\left(1+\frac{s}{8\pi T}\right)\Gamma\left(1+\frac{t}{8\pi T}\right)\Gamma\left(1+\frac{u}{8\pi T}\right)} \quad \text{........................ (26)}$$

where p_1, p_2, p_3, p_4 are the external momenta and s, u, t the Mandelstam invariants[35]

$s = (p_1 + p_2)^2$ .... (27)

$t = (p_1 + p_4)^2$

$u = (p_1 + p_3)^2$

Eq. (26) shows that for s, t, u <<T, string field theory reduced to point like field theory. Physically, the tiny string of dimension d~10^{-33} cm appears as points when looked coarsely, but their non zero extension is crucial at very small distances.

To measure such a tiny string-like nature of low energy effective point-like particle like electron is a far cry at the moment. HERA experiments at DESY, Hamburg with 27.5 GeV positrons colliding with 820 GeV proton could probe upto a distance of 10^{-16} cm only.[36]

In recent years[37] theorists are getting interested about description of physics in terms of multidimensional 'branes'. In this language, instead of a particle, electron at low energy is a 0-brane while at Planck scale, it is a 1-brane.

Let us comment on the possibilities of a Planckian accelerator to measure a distance of 10^{-33} cm in near or far future. To this end, let us take a look at the past history of accelerators. This is studied through the Livingstone Chart38, where the logarithm of energy E is plotted against time. Since the plot is a straight line, we can write

$\log E = \log E_0 + bt$ .... (28)

where the slope parameter b is given by

$$b \approx \frac{1}{6}(year)^{-1} \quad \text{.......................(29)}$$

So in every six years, the energy of the accelerator increases by a factor 10. We can interpret this exponential growth of the energy as an optimistic sign for future accelerator physics.

Fixing, E_o in Eq. (28) by the value of $E_o \approx 100$ KeV (Cockroft and Walton generator) at t ≈ 1930 AD,

$$\log\left(\frac{E}{100KeV}\right) = \frac{1}{6}(t - 1930)$$

$$E \sim (100KeV)10^{\frac{1}{6}(t-1930)} \qquad \text{.......................(30)}$$

where t is in years.

For fixed target mode, E is the energy of the accelerator, $E_{lab.}$ For the collider, E is the equivalent laboratory energy given by

$$E_{lab} = \frac{E_{cm}^2}{2m_p} \qquad \text{.......................(31)}$$

where E_{cm} is the centre of mass energy and m_p is proton target mass.

To reach Planck energy 10^{19} GeV, in the cm system, we need the effective lab energy E given by

$$E \approx \frac{(10^{19})^2}{2m_p} \sim 10^{38} GeV \qquad \text{.......................(32)}$$

Substituting it in (30) we get

t–1930 ≈ 252 years

So in the year 2182 AD, we can test the string like nature of electron!

A more nearer Planck year can be obtained by taking $E = E_{cm}$ for the colliders. Taking the same slope of $\frac{1}{6}(year)^{-1}$, we take E_o = 14 TeV corresponding to the full energy of future LHC[39] in the year 2008. We can therefore write

$$\log \frac{E}{14TeV} = \frac{1}{6}(t - 2008) \qquad \text{.......................(33)}$$

Putting E = 10^{19} GeV, we get

$$t–2008 = 90$$

giving

$$t = 2008$$

It implies, we may reach Planck Energy before the end of the next century. At least till then, perhaps possible string structure will not be feasible experimentally. But that is not too far either[41-43].

Concluding Remarks

We have briefly discussed the status of electron as the fundamental particle. Till now, no significant deviation from its pointlike elementary structure has been detected. Perhaps many order of magnitude high energy accelerators will be needed to detect its possible substructures, pointlike or stringy.

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