

THE ELECTRON, MUON, AND TAU HEAVY LEPTON:
ARE THEY THE TRULY ELEMENTARY PARTICLES?*

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Physicists and philosophers have long been searching for the ultimate nature of matter. Thus Democritus, who lived about 460 BC to 370 BC, taught that all matter consists of atoms. He thought of atoms as permanent, impenetrable, invisible, and most important--as incapable of being subdivided into simpler entities. The purposes of this article are: first, to discuss our present concept of the ultimate nature of matter--the elementary particle; second, to explain why the lepton family of particles--the electron, muon, and tau--may be truly elementary and third to describe the recently discovered tau lepton in more detail.

Atoms, Nuclei, and Particles

Atoms, as we define them today, are not the atoms of Democritus; they are not permanent, they can be penetrated, and they are comprised of simpler particles. We know that an atom consists of (a) a central core called a nucleus with a radius roughly a few times 10^{-13} cm; and (b) one or more electrons moving around the nucleus in orbits whose radii are roughly 10^{-8} cm. As shown schematically in Fig. 1 the nucleus itself is composed of simpler particles, namely neutrons and protons. The only

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exception to this rule is the hydrogen nucleus which is a single proton. The radius of a neutron or proton is about 10^{-13} cm. (Since the neutrons and protons in a nucleus are packed closely together, the nuclear radius is just a few times larger as we noted above.)

Until about fifteen years ago, physicists believed that particles such as the neutron and the proton were not composed of other particles. We now have very strong, but indirect, evidence that this is not so; we believe that neutrons and protons are clusters of particles called quarks. Hence we consider the quarks to be simpler, or in physicist's terms more elementary, than the neutron or proton. I will return to the quarks later in this article.

Returning to Fig. 1, notice that there is no sequence of increasingly simpler particles attached to the electron. As far as we know the electron cannot be subdivided into simpler particles; the electron is as simple as a particle can get. Furthermore in contrast to the neutron or proton, the radius of the electron is less than 2×10^{-16} cm; indeed the electron acts as though it is a mathematical point. Those differences in simplicity and size between the electron on the one hand and the neutron or proton on the other hand, are the crux of why we consider the electron to be elementary but not the neutron or proton.

Elementary Particles: Concept and Experiment

Our present definition of an elementary particle requires:

1. that the particle not be composed of simpler particles; and
2. that the particle have no internal structure

In science we must give our definitions reality by associating experimental tests with the definition; that is, we must be able to

determine by experiment if a particle is elementary. The method most often used is the scattering of one particle off another particle. I will explain this using the example of the scattering of an electron off a proton. Indeed, this experiment has been carried out repeatedly in the past twenty years; and it led to the discovery of quarks.

In Fig. 2a a high energy electron coming from an accelerator is traveling towards a stationary proton. If the electron passes many proton radii away from the proton, Fig. 2a, the only force between the particles is the electrical attractive force between the negative electron charge and the positive proton charge. The result, Fig. 2b, is that the electron is deflected towards the proton as it passes it, and the proton also begins to move. Thus the electron has scattered off the proton.

Next consider the situation when the electron's path takes it thru the proton, Fig. 3a. Here a new thing can happen. When the electron hits the proton, the proton often breaks up into other particles called hadrons, Fig. 3b. In fact, if the electron has enough energy, five or ten or twenty hadrons can be made. [I'll say a little about hadrons in the next section.] The electron comes out of the collision with its path deflected, as we expect.

However, if we measure in detail how the electron is deflected, we find that the proton does not have a uniform distribution of matter. Instead almost all the matter of the proton is concentrated in three very hard and very small particles inside the proton--the quarks. The proton breaks up when the electron passing thru the proton hits one of the quarks. This is how we know that a proton is not an elementary particle.

Now consider the case when one electron is scattered off another electron. We always find the situation in Fig. 4. That is, we can never get one electron to pass thru another electron. The electrons are so small that they always miss each other and so are merely deflected by each other. Furthermore we have never been able to break up electrons the way we break up protons. Thus to the best of current experimental knowledge; the electron is not composed of simpler particles; and the electron has no internal structure because it has no measurable size. Present experiments set the size of the electron at less than 2×10^{-16} , that is, less than 1/500 of the size of the proton. Hence the electron is an elementary particle.

Hadrons and Leptons

The proton and the electron are representative of two of the three known families of elementary particles: the hadrons and the leptons respectively. The third family contains the photon, which is the particle associated with electromagnetism. Other members of the photon family have yet to be experimentally discovered, and I won't say any more about the photon family.

The hadron family is vast, almost one hundred types of hadrons have been found. A few of the best known are listed in Table 1, where their masses are given in terms of equivalent energy units--MeV. [The MeV (Million electron Volts) is the energy acquired by an electron which is accelerated through a million volts.] The pion is the hadron with the smallest mass; and when a high energy electron breaks up a proton, most of the hadrons produced are pions. The largest mass hadron so far

discovered is the upsilon (T) with a mass of about 10,000 MeV. As far as we know, heavier hadrons can exist; we know of no theoretical limit to the mass that a hadron can have.

All hadrons have about the same size as the proton, 10^{-13} cm; and all hadrons are composed of quarks. Therefore hadrons are not elementary particles. This fits well with our hope that the basic nature of matter is simple and elegant. If the almost hundred kinds of hadrons were elementary, the basic nature of matter would be very complicated.

The lepton family, Table 2, is much less numerous than the hadron family; only six types of leptons have been discovered. There are three electrically charged leptons: the electron (e), the muon (μ), and the recently discovered tau (τ). And there is an electrically neutral lepton--the neutrino--associated with each charged lepton. Hence there are three types of neutrinos; making six lepton types in all. To the best of our current knowledge all leptons are elementary particles. Like the electron, they do not contain simpler particles. And like the electron they have no measurable size. The e , μ , and τ act like mathematical points with radii less than 2×10^{-16} cm. It is difficult to measure the size of the neutrinos; however their radii are less than 2×10^{-15} cm; and to the best of our knowledge they also act as mathematical points.

Before turning to a more detailed discussion of the leptons, I will discuss the different behaviors of leptons and hadrons with respect to the strong force, one of the four basic forces.

The Four Basic Forces

There are four basic forces between particles:

- 1) The Gravitational Force: Gravity acts on both hadrons and leptons.

- 2) The Electrical Force: The electrical force acts on both leptons and hadrons as long as they contain electrical charge.
- 3) The Weak Force: This is the most unfamiliar force of the four forces for two reasons. First, it only exists between particles when they are closer than about 10^{-13} cm. Hence it has very small effects on atomic spectra and phenomena. Second it is usually overwhelmed by the strong force (discussed next) which also acts at distances less than 10^{-13} cm. However it can be detected in several ways. The beta decay of nuclei occurs because of the weak force; and neutrinos interact with other particles thru the weak force. Both leptons and hadrons are acted upon by the weak force.
- 4) The Strong Force: The strong force, often called the nuclear force, is the force that binds the neutrons and protons together in the nucleus. It is called strong because it holds the nucleus together against the mutual electrical repulsion of the protons in the nucleus. From a more basic viewpoint the strong force controls the properties of all the hadrons. It binds the quarks in the hadron together. And it is the underlying cause of the proton breaking up into hadrons when it is struck by another high energy particle. All in all, the strong force makes the properties and behavior of all the hadrons very complex. However the strong force does not act on leptons. This has two consequences. First, the insensitivity of the leptons to the strong force separates the leptons from the hadrons. Second, the absence of the

strong force simplifies the properties and behavior of the leptons. Thus it is relatively easy to study the basic properties of the leptons.

The "Old" Leptons: The Electron, Muon, and their Neutrinos

The electron was discovered in the 1890's by J.J. Thomson in his famous cathode ray tube experiments. It took forty years for the second electrically charged lepton, the muon (μ), to be discovered in cosmic rays. As I have already noted the electron and muon share many properties in common: they both behave as mathematical points; they both are acted upon by the gravitational, electrical, and weak force, but not by the strong force; and they are both elementary particles. But the mass of the muon is about 200 times the mass of the electron!

This mass ratio of about 200 dramatically emphasizes one of the fundamental unsolved problems of particle physics: What sets the mass of a particle? If the electron and muon are so alike, why is the muon so much more massive? To add to the puzzle, the electrically neutral partner of the electron, the electron neutrino (ν_e) has a mass much smaller than the electron; indeed it may have zero mass. All we know for sure is the upper limit on the mass given in Table 2. The muon neutrino (ν_μ), the electrically neutral partner of the muon, also has a mass close to zero or perhaps exactly zero.

Note that the four leptons so far discussed have masses less than the mass of the pion (140 MeV), and recall that the pion is the hadron with the smallest mass. Until about five years ago it was thought that perhaps an intrinsic property of the leptons was that their masses were small compared to hadron masses. Indeed the name lepton comes from the

Greek word lepto meaning light or fine. We shall see that the name lepton is really a misnomer.

The sceptical reader might ask, "If the electron neutrino and muon neutrino both have zero mass, what differentiates them?" The present unsatisfactory answer is that we know experimentally that they are different. When an electron neutrino interacts with matter it can come out again as an electron neutrino or it can change into an electron. But it never comes out of the interaction as a muon neutrino or as a muon. Conversely the interaction with matter of a muon neutrino can lead to a muon neutrino or a muon coming out; but it never leads to an electron neutrino or to an electron coming out.

The electron neutrino has an "electronness" property; a muon neutrino has a "muonness" property; and these are completely separate properties. "Electronness" and "muonness" are also properties of the electron and muon themselves. Electrons only connect to other electrons or to electron neutrinos. Muons only connect to other muons or to muon neutrinos. We don't understand "electronness" and "muonness" in a fundamental way; we only know that the $e-\nu_e$ and $\mu-\nu_\mu$ are separate subgroups of the lepton family and that these subgroups do not interact with each other.

The Tau Heavy Lepton

About five years ago my colleagues and I began to look for heavier, that is more massive, leptons using the electron-positron colliding beam machine SPEAR at the Stanford Linear Accelerator Center. I was following an old idea in science: If you can't understand a phenomena look for more examples of the phenomena. We couldn't understand what set the

masses of the leptons; and we couldn't understand "electronness" and "muonness."

When we began the search we didn't know if heavier leptons existed; and we didn't know if we were looking in the right mass range. Thus it was to our surprise, and I think to the greater surprise of other particle physicists, that we found a new electrically charged lepton which we named the tau (τ). The name comes from the first letter of the Greek word triton meaning third; the tau being the third charged lepton to be discovered.

The astonishing property of the tau is its mass of 1782 MeV. It is heavier than many hadrons. Thus the old idea was wrong that leptons had to have small masses. In spite of its relatively large mass it is an elementary particle. It is not composed of simpler particles; and its size is like the electron size, less than 2×10^{-16} cm. Also it fits the definition of a lepton because it is acted upon by the electrical and weak forces, but not by the strong force. (We expect that it is also acted upon by the gravitational force, but it is very difficult to test that.)

Just as the electron and muon possess mysterious and unique qualities which I have called "electronness" and "muonness," so the tau possesses a unique quality which I call "tauness." And there is a neutrino associated with the tau (ν_{τ}) which also possesses "tauness."

We know less about the tau neutrino than we do about other neutrinos because all this is so new. We believe the tau neutrino is uniquely associated with the tau but the experimental tests of this belief are much less extensive than are the tests that prove that the electron neutrino is uniquely associated with the electron. Also, as

shown in Table 2, the mass of the tau neutrino is smaller than the mass of the tau but we still have a long way to go to prove that the tau neutrino has a mass as small as that of other neutrinos.

The Truly Elementary Particles

Thus from everything we have measured about the leptons we believe that they are a family of truly elementary particles. They are not the only family of elementary particles. The quarks are probably also elementary, but the strong force makes it difficult to study basic properties of the quarks such as their mass.

Our tasks with respect to understanding the leptons are clear. First, we must continue to look for more leptons. Some physicists believe there are no more, or only a few more, lepton types. However we do not know a fundamental limit on the number of lepton types which can exist. Second, some bright young woman or man, some new Einstein, must look at what we know about the leptons; and must tell us what sets the masses of the leptons, and what is "electronness," muonness" and "tauness."

FIGURE CAPTIONS

1. Schematic of the particles in an atom. The nucleus is made up of protons and neutrons; and those are made up of quarks. Therefore the atom, nucleus, proton, and neutron are not elementary particles, but we believe the quarks are elementary particles. On the other hand the electron is not made up of simpler particles and it is elementary.
2. If a high energy electron is moving past a proton as in (a); then the electron and proton simply scatter off each other as in (b). The dashed lines show the particle paths. The electron path is bent towards the proton and the proton moves towards the electron because their opposite electric charges attract each other.
3. If a high energy electron moves into a proton as in (a); then the proton often breaks up into many hadrons as in (b). The electron is also deflected as represented by the dashed line in (b).
4. In (a) a high energy electron is moving directly into another electron. However all that happens is that they scatter off each other as in (b). The electrons move away from each other because their like electric charges produce a repulsive force.

Table 1. A few of the hadrons. Their masses are given in terms of the equivalent energy unit, MeV.

Name	Symbol	Mass (MeV)
pion	$\pi^{\pm,0}$	π^{\pm} 140. π^0 135.
rho	$\rho^{\pm,0}$	770.
proton	p^+	938.3
neutron	n^0	939.6
psi/J	ψ/J^0	3097.
upsilon	T	9460.

Table 2. The known leptons. Their masses are given in terms of equivalent energy units, MeV.

Charged lepton name	electron	muon	tau
Charged lepton symbol	e	μ	τ
Date of discovery of charged lepton	1890's	1930's	1974-1975
Charged lepton mass (MeV)	0.51	106.	1782 ± 4
Charged lepton lifetime (seconds)	stable	$2.2. \times 10^{-6}$	less than 1.4×10^{-12}
Associated neutrinos	$\nu_e, \bar{\nu}_e$	$\nu_\mu, \bar{\nu}_\mu$	$\nu_\tau, \bar{\nu}_\tau$
Associated neutrino mass	less than 60 eV*	less than 0.57 MeV	less than 250. MeV

* eV = electron volt = $10^{-6} \times$ MeV

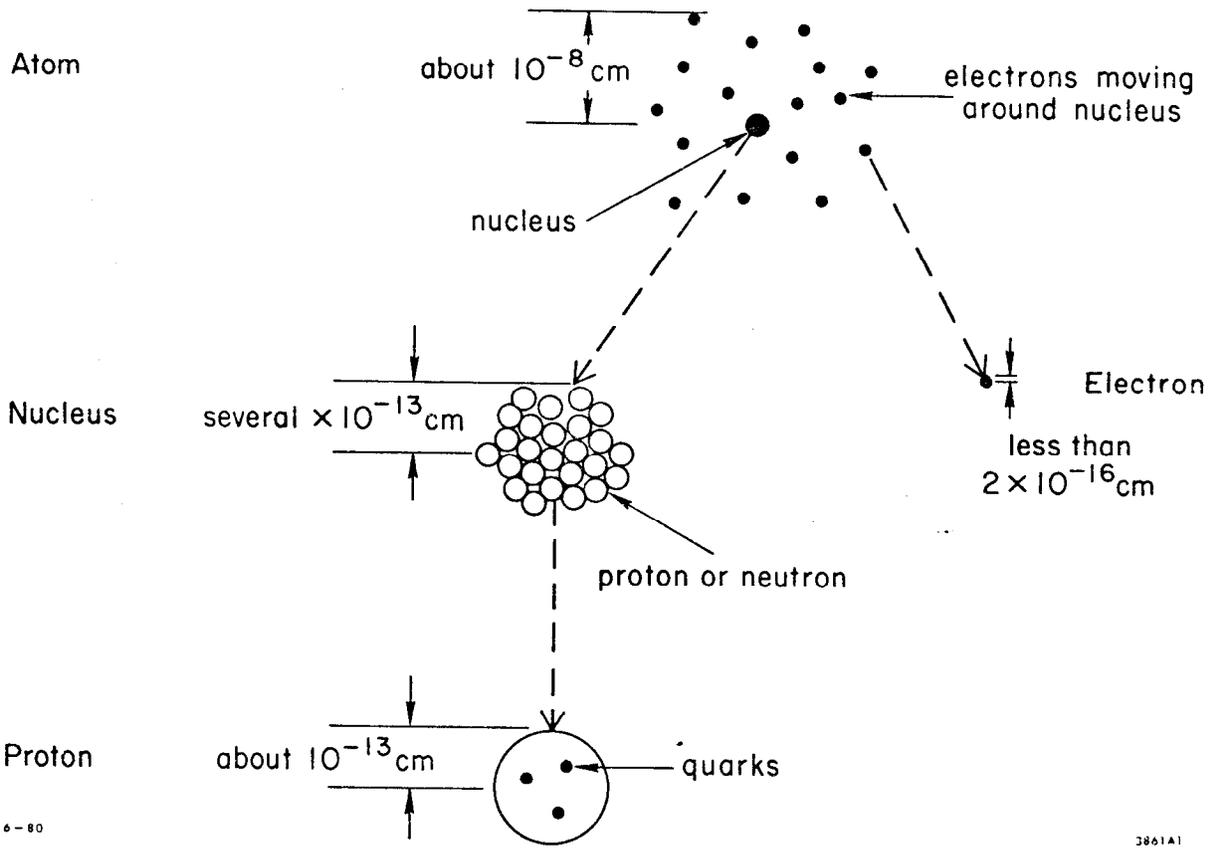
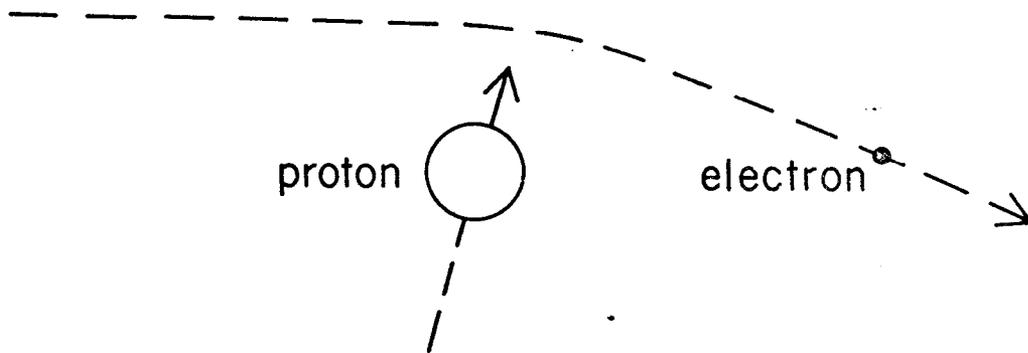


Fig 1

electron →

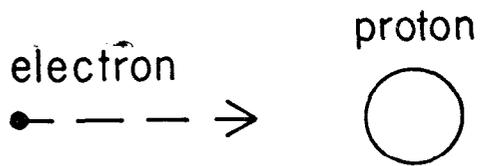
proton ○

(a) Before scattering

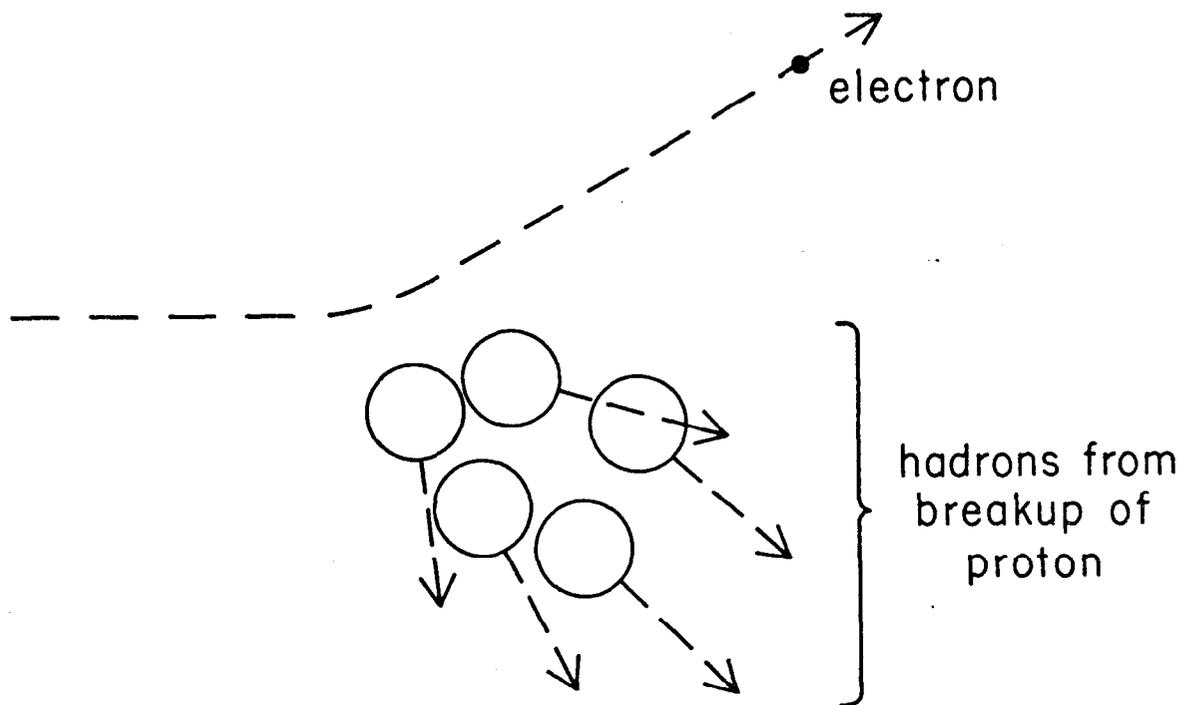


(b) After scattering

Fig. 2



(a) Before scattering

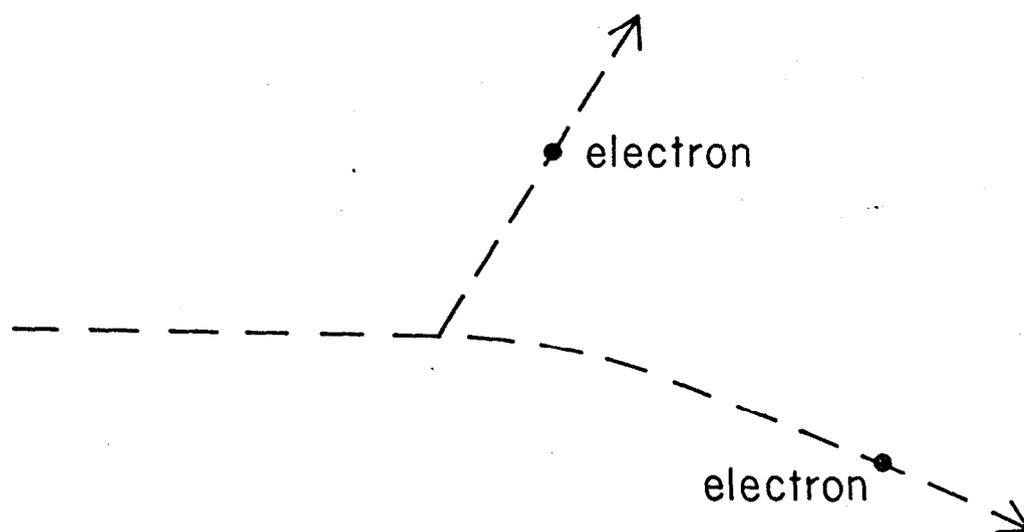


(b) After scattering

Fig. 3



(a) Before scattering



(b) After scattering

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Fig. 4