Origin of Mass

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Abstract

Thousands of physicists are working night and day to solve an even more fundamental problem. How do particles acquire mass? Although many of us would like to have less mass, particle theorists find it extremely difficult to explain how we have any at all. In this paper I attempt to explain the formation of mass by different approaches which may clarify the concept of mass.

Key words: *Higgs field, Quanta, Relativity, emergent mass, Quantum chromo-dynamics, Photon*

Introduction

The origin of mass is one of the most intriguing mysteries of nature. Some particles, such as the W boson (which carries the weak force) have so much mass they barely move, while others, like the photon, are entirely massless and zip around at the speed of light. The story of particle mass starts right after the big bang. During the very first moments of the universe, almost all particles were massless, traveling at the speed of light in a very hot "primordial soup." At some point during this period, the Higgs field turned on, permeating the universe and giving mass to the elementary particle**s [1].**

What is mass?
Newtonian Mass:

In classical physics, as epitomized in Newtonian mechanics, mass is a primary, conserved and irreducible property of matter. Reflecting that significance, Newton spoke of mass as quantity of matter [**2**]. Mass was so foundational within Newton's view of the world that he took its central feature what I call Newton's zeroth law of motion – for granted, without stating it explicitly. Newton's zeroth law of motion, which underpins use of the others, is the conservation of mass. The Newtonian mass of a body is assumed to be a stable property of that body, unaffected by its motion. In any collision or reaction, the sum of the masses of the incoming bodies is equal to the sum of the masses of the products; mass can be redistributed, but neither created nor destroyed. Mass also occurs, of course, in Newton's gravitational force law. Newtonian mass is, in fact, the new primary quality of matter introduced into the foundation of classical physics. It supplements size and shape, which the strict "mechanical philosophy" of *Descartes* and of many of Newton's scientific contemporaries had claimed should be sufficient [**2**]. Relativity, and then quantum field theory, profoundly changed the status of mass within physics. Both main properties of Newton's mass-concept got undermined. In special relativity we learn that

energy is conserved, but mass is not. In general relativity we learn that gravity, in the form of space-time curvature, responds to energy, not to mass. The word mass still appears in modern physics, and the modern usage evolved from the earlier one, but it denotes a radically different, more fluid concept. Though these profound changes began in earnest more than a hundred years ago, the old concept of mass remains deeply embedded in common language and in the folk physics of everyday life, not to mention in successful engineering practice. The demotion of mass from its position as a logical primitive in the foundation of physics challenges us to rebuild it on deeper foundations, and opens up the central question of this paper: What is the Origin of Mass?

Relativistic Mass

In modern physics energy and momentum are the primary dynamical concepts, while mass is a parameter that appears in the description of energy and momentum of isolated bodies [**3**]. The early literature of relativity employed some compromise definitions of mass – specifically, velocity-dependent mass, in both longitudinal and transverse varieties. Those notions have proved to be more confusing than useful. They do not appear in modern texts or research work, but they persist in some popularizations, and of course in old books. To forestall confusion about the facts and definitions, the concept of standard relativistic mass has discussed. This will also be an opportunity to highlight an elementary but profound point that is widely overlooked.
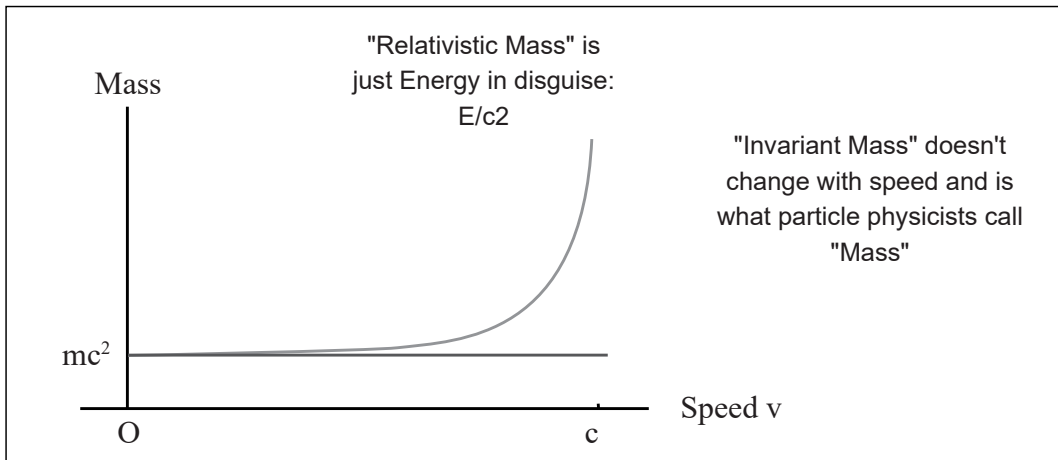

Fig 1: The two interpretations of mass, invariant mass (green) and relativistic mass with speed. [**4**]

Mass is something that does not change with speed often called invariant or rest mass and the relativistic mass is just energy divided by c-squared, and grows with speed. Note that two are almost identical at small velocities , and so are usually equal in daily life .
Let us contrast the Newtonian and relativistic equations for momentum, in terms of mass m and velocity v

Then, Newtonian inertia   ,
$$P_N = mv \qquad \qquad ... \ (1)$$

Relativistic Inertia ,
$$P_R = \gamma mv \qquad \qquad ... (2)$$

where, $\gamma = \dfrac{1}{\left(1-\dfrac{v^2}{c^2}\right)}$,the relativistic parameter .

Where c is the speed of light. p is a measure of the body's resistance to acceleration, or inertia. Both Newtonian and Einsteinian   mechanics posit that different observers, who move at constant velocity relative to one another, construct equally valid descriptions of physics, using the same laws. To two such observers the body appears to move with different velocities, and also to have different momenta, but both observers will infer the same m. Similarly, for the energy
we have , $E_N = \frac{1}{2} mv^2$ Newtonian kinetic energy   ... (3)

$$E_R = mc^2 \, \dfrac{1}{\sqrt{1-\dfrac{v^2}{c^2}}} \qquad \text{Relativistic energy} \qquad ... (4)$$

The relationship between Eqns. (1, 2) is straightforward: For v c, Eqn. (2) goes over into Eqn. (1). Not so the relationship between Eqns. (3, 4). Expanding E_R for v << c ,
we have approximately
$$E_R \approx mc^2 + m^2 v^2 = mc^2 + E_N \qquad \qquad ... (5)$$
The first term on the right-hand side of Eqn. (5) is of course the famous mass-energy $E = mc^2$ associated with bodies at rest.
Now consider two slowly-moving bodies that interact with each other weakly, so that we can neglect potential energy. If only conservation (i.e., constancy) of the total energy is
Assumed,
$$E_{R,\, total} \approx m_1 c^2 + 1/2 m_1 v_1^2 + m_2 c^2 + 1/2\, m_2\, v_2^2 \qquad \qquad ... (6)$$

then we can't deduce that m_1, m_2, or even $m_1 + m_2$ is rigorously constant, nor that the Newtonian kinetic energy $1/2 m_1 v^2 + 1/2 m_2\, v^2$ is constant. Formal hocus-pocus can't conjure up three independent conservation laws from just one! Rather, it would be natural to expect, from Eqn. (6), that small changes in m_1 and m_2 could accompany the dynamical evolution. Alternatively: Eqn. (6) in itself does not explain why the Newtonian kinetic energy, which after all is the second, sub dominant term in the expansion of E_R, should be separately conserved, even approximately. All that we can legitimately infer is that if the bodies move slowly, with v <<c for both v = v_1, v_2, then $m_1 + m_2$ is approximately constant, to order v^2/c^2 . Indeed, if we divide Eqn. (6) through by c ^{2},

Implied that , $E_{R,total}/c^2 \approx (m1 + m2)(1 + order\ v^2 /c^2)$ ... (7)

These difficulties of principle actually come into play in describing nuclear reactions, where neither mass nor Newtonian kinetic energy is separately conserved, even when all the bodies involved move slowly. In the most radical departure from the Newtonian framework, we are allowed to consider bodies with zero mass. (And, as we'll see, that possibility proves to be very fruitful.)

The momentum and energy P_R, E_R can have sensible, finite limits as m → 0, with v → c appropriately. Thus isolated bodies with m = 0 move at the speed of light, and for such bodies we have

$$P_R = E_R/c \qquad\qquad\qquad ... (8)$$

but no other restriction on the values of P_R or E_R. These considerations sharpen the challenge of understanding the emergence of Newtonian mass as a valid approximation in the physical world.

Masses of Quanta

Relativistic quantum field theory introduces a powerful constructive principle into the reductionist program [1]. Since quantum fields create (and destroy) particles, space-time uniformity of the fields i. e. their invariance under space and time translation – implies that their associated particles will have the same properties, independent of where and when they are observed. Thus all electrons, for example, have the same properties, because they are all excitations of a single universal quantum field, the electron field. Thoughtful atomists, notably including Newton and Maxwell, were highly aware that the most elementary facts of chemistry – that is, the exact reproducibility of chemical reactions, including their intricate specific rules of combination – called for the building blocks of matter to have this feature of accurate sameness, or universality, across space and time. The macroscopic bodies of everyday experience, of course, do not – they come in different sizes, shapes, and composition, and can accrete or erode over time. In our ordinary experience, only artfully manufactured products can approximate to uniformity. Both Newton [5] and Maxwell [6] inferred that the basic building blocks of matter were manufactured by God at the time of creation. Modern quantum field theory opens the possibility of an alternative explanation. For our problem of the origin of mass, this general principle gives most welcome simplification and guidance [1]. Rather than having to address the mass of each object in the universe separately, we can focus on the properties of a few quantum fields, whose excitations (quanta) are the building blocks of matter. Thus for instance if we understand the properties (including mass) of one electron we understand the properties of all electrons. More generally: If we understand the properties of the fields associated with the building blocks of matter, we should be able to deduce the properties – including mass! – of matter itself, and those deductions will be valid universally.

Emergent mass:

Since the time quantum theory was originally formulated there have been many attempts to unite it with general relativity. As gravitational interactions are a consequence of malleable space-time, proposals were put forward that space-time is a purely macroscopic concept that somehow emerges from the underlying microscopic quantum degrees of freedom. For example, the spin network idea of Penrose [3] posits that the continuous array of directions in 3D space emerges out of the quantum concept of spin in the limit of large quantum numbers. Since elementary particles exhibit other quantized properties beside that of spin, a simple extension of Penrose's idea would be to take them into account as well. Thus, one might hope that the

inclusion of other spatial quantum numbers, internal quantum numbers and quantized particle masses should somehow lead to the emergence of further features of classical space-time [1].

In particular, with mass being the source of gravity-inducing space distortions, it seems quite natural that the quantized mass should play an important role in the emergence of classical space-time out of the quantum layer. Since a successful theory of mass and space quantization should express all particle masses in terms of one mass scale (say, Planck mass), elementary particle masses give us important experimental clues on space quantization itself - clues that are completely inaccessible at the minuscule Planck length scale.

Higgs mass:

Scottish theorist Peter Higgs postulated that particles acquire mass by scattering off of a particle that fills all space, now called the Higgs Boson. The heavier the individual particle, the more often it will interact with the Higgs. Think of a politician moving through a crowd. The more popular she is, the more people will try to shake her hand. In analogy, the heavy top quark interacts constantly by scattering off of Higgs particles, while the light electron moves through the crowd with only an occasional handshake.

The Higgs mechanism plays a key role in the physics of elementary particles: in the context of the Standard Model, the theory which describes in a unified framework the electromagnetic, weak and strong nuclear interactions, it allows for the generation of particle masses while preserving the fundamental symmetries of the theory. This mechanism predicts the existence of a new type of particle, the scalar Higgs boson, with unique characteristics. The detection of this particle and the study of its fundamental properties is a major goal of high–energy particle colliders, such as the CERN Large Haddon Collider or LHC.[14]
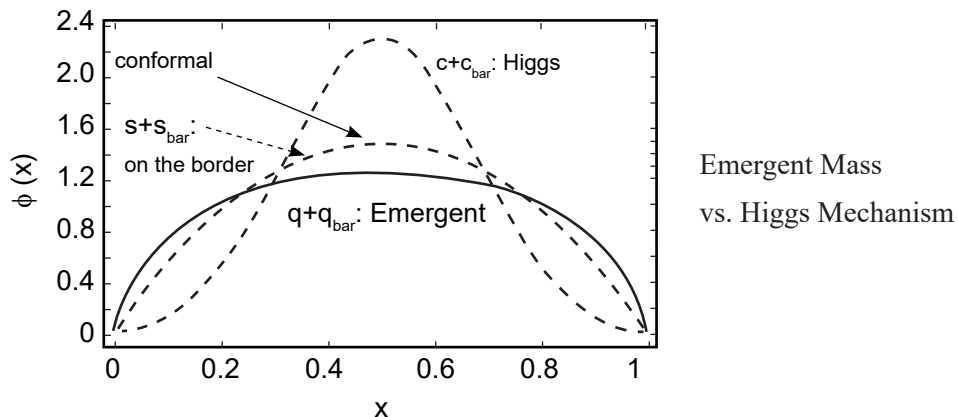

Fig 2: Comparison between distributions of light quarks and those involving strange quarks for strong mass generation. [**10, 14**] *https://doi.org/10.1063/1.4715399*

Of course, it is quite possible that neither the Tevatron nor the LHC will observe the Higgs boson. There may even be several Higgs particles, in addition to new partners for all of the known fundamental particles. And, if neutrinos are confirmed to be their own antiparticle in double beta-decay experiments, the Higgs mechanism cannot explain neutrino masses, replacing one mystery with another. This may provide the most exciting scenario of all for particle physicists:

the opportunity to discover new particles and the laws that govern them.

All 60 virtual particles in the shell of each proton are principally indistinguishable from each other. According to generally accepted particles classification they belong to the group of bosons. The particles in the composition of virtual shells of real elementary particles and atomic nuclei actually generate more than 99% of ordinary matter mass. Namely, it is just the main property of the Higgs bosons. [5,6]

It is crucial that the bosons in the virtual shells do not have any own masses. As we have seen along the whole Periodic table their contribution to real mass generation depends on the number of such virtual particles in concrete shell. That is why in standard theory mass of Higgs boson itself remained unknown. At the same time in the experiment it is impossible to separate bosons own mass and its contribution to the total mass of the real particle. In such situation the experimentally measured value must radically depend on what real particles were used as a target. A unique feature of the Higgs boson is that it creates a mass of other particles, but does not have any own mass. It seems to be obvious that only particle with such combination of properties by definition may be called the Creator of mass.

Generation of real mass is a result of interaction between virtual shells particles and specific field. In absentia it was called the Higgs field. Fundamentally it is just alternating gravitational field. About its properties we know very small, but enough to suggest that the most intriguing modern mysteries of biology and other sciences are directly connected with alternating gravitational fields. In such fields arise very considerable strengths, evident traces of their action are obviously seen.

Concept of Negative masses
 why negative masses are necessary and why they are possible? It is obvious that only particles with negative mass can generate attractive forces as result of exchanging interactions. The exchange of vector bosons leads to the appearance of attractive forces only because inside their structure exist components with negative mass, as we have seen above.

For elementary particles the concept of negative mass must be understood in a special sense. Existence of elementary particles not in empty space, but surrounded by physical vacuum inevitably changes the zero level of mass determining. In any real experiment it is impossible to provide selective force exerted on certain pre-selected elementary particle. Only force field in the surrounding space can be created.
The action of the gravitational field on elementary particle surrounded by vacuum conventionally can be compared to behavior in water steel balls and air bubbles. Actually air bubbles demonstrate only illusion of the negative mass, the air bubbles move against the forces of the gravitational field due to the force of Archimedes. But obvious understanding of the true situation is based on using concepts of density to water and air. To elementary particles and to physical vacuum mechanical concept of density is not applicable and adequate replacement does not exists.[**11**]

In such a situation the zero level of mass determining is shifted and appears the illusion of negative mass. In vector bosons structure there are components whose interaction with the external gravitational field is weaker than that of the virtual vacuum particles. And just these structural components demonstrate the illusion of negative mass. This is a forced compromise due to lack of knowledge and imperfection of the conceptual apparatus. But compared with the representation of particles as mathematical points this seems a definite step forward.

Conclusion

Newtonian mechanics posited mass as a primary quality of matter, incapable of further elucidation. We now see Newtonian mass as an emergent property. Most of the mass of standard matter, by far, arises dynamically, from back-reaction of the color gluon fields of quantum chromo-dynamics [10]. The equations for mass less particles support extra symmetries - specifically scale, chiral, and gauge symmetries. The consistency of the standard model relies on a high degree of underlying gauge and chiral symmetry, so the observed non-zero masses of many elementary particles (W and Z bosons, quarks, and leptons) requires spontaneous symmetry breaking**.**

Superconductivity is a prototype for spontaneous symmetry breaking and for mass-generation, since photons acquire mass inside superconductors. A conceptually similar but more intricate form of all-pervasive (i.e. cosmic) superconductivity, in the context of the electroweak standard model, gives us a successful, economical account of W and Z boson masses. It also allows a phenomenologically successful, though profligate, accommodation of quark and lepton masses. The new cosmic superconductivity, when implemented in a straightforward, minimal way, suggests the existence of a remarkable new particle, the so-called Higgs particle [**12,13**]. The mass of the Higgs particle itself is not explained in the theory, but appears as a free parameter. Earlier results suggested, and recent observations at the Large Hadron Collider (LHC) may indicate, the actual existence of the Higgs particle, with mass mH≈125 GeV. In addition to consolidating our understanding of the origin of mass, a Higgs particle with mH≈125 GeV could provide an important clue to the future, as it is consistent with expectations from super symmetry.

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