Relativistic Mass is an Experimental Fact

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Abstract

Since mass is defined as the measure of the (experimentally established) *resistance* a particle offers to its acceleration and as it is also an experimental fact that a particle's resistance to its acceleration increases when its velocity increases, it follows that, like mass, the concept of relativistic mass also reflects an experimental fact. This means that the rejection of the relativistic velocity dependence of mass amounts to both rejection of the experimental evidence and refusing to face and deal with one of the deepest open questions in fundamental physics – the origin and nature of the inertial resistance of a particle to its acceleration, i.e., the origin and nature of its inertial mass.

This leads to a complete confirmation of the relativistic [mass] formula, which can thus be considered as experimentally verified. Pauli [1].

During the last four decades physicists have endured "what has probably been the most vigorous campaign ever waged against the concept of relativistic mass"[1] by some overconfidant (mostly particle[2]) physicists, which, regretfully, still continues. It will probably go down in the history of physics as un unfortunate collective attempt to reject a concept firmly supported by experimental physics.

As a result, the status of relativistic mass constitutes an unprecedented situation in physics. Some physicists firmly reject this concept, whereas others continue to regard it as one of the novel concepts introduced by special relativity. This division within the physics community still persists despite publications[3] specifically dealing with the concept of mass.

What is also unprecedented is that the rejection of the concept of relativistic mass is based on the almost open rejection of the accepted definition of mass (the measure of the *resistance* a body offers to its acceleration) without specifying what definition of mass is used. Max Born explicitly warned about the danger of improper understanding of mass in relativity [6]:

[1]For an account of the controversy over relativistic mass see Chapter 2 of Max Jammer's excellent book *Concepts of Mass in Contemporary Physics and Philosophy* [2].

[2]It seems rather ironic that some particle physicists reject the velocity dependence of mass given that the overwhelming experimental confirmation of that dependence is provided by particle accelerators.

[3]In the *American Journal of Physics* [3], *Physics Today* [4] and the *Physics Teacher* [5]

In ordinary language the word mass denotes something like amount of substance or quantity of matter, these concepts themselves being defined no further... In physics, however, as we must very strongly emphasize, the word mass has no meaning other than... the measure of the resistance of a body to changes of velocity.

Taking into account the accepted definition of mass, which reflects the experimental fact that a particle resists its acceleration,[4] unambiguously demonstrates that relativistic mass also reflects an experimental fact – the *increasing* resistance of a particle to its acceleration when the particle's velocity increases.[5] It is this increasing resistance (i.e., its increasing mass) that prevents a particle from reaching the velocity of light. This profound role of relativistic mass makes it an integral part of spacetime physics.

Perhaps the best summary of the role of the velocity dependent mass in spacetime physics was given by Feynman [7, p. 15-9]:

What happens if a constant force acts on a body for a long time? In Newtonian mechanics the body keeps picking up speed until it goes faster than light. But this is impossible in relativistic mechanics. In relativity, the body keeps picking up, not speed, but momentum, which can continually increase because the mass is increasing. After a while there is practically no acceleration in the sense of a change of velocity, but the momentum continues to increase. Of course, whenever a force produces very little change in the velocity of a body, we say that the body has a great deal of inertia, and that is exactly what our formula for relativistic mass says (see Eq. 15.10[6])—it says that the inertia is very great when v is nearly as great as c.

Feynman did not say it explicitly, but his explanation is clear – the physical meaning of "the body has a great deal of inertia" is "the body offers a great deal of *resistance* to its acceleration;" therefore the body has increasing mass that does not allow it to move as fast as light.

In hindsight, the mechanism that prevents a particle from reaching c was, in fact, present in Newtonian mechanics, where mass is defined as the measure of the resistance a particle offers to its acceleration. When Einstein postulated that the velocity of light c is the greatest velocity a particle (with non-zero rest mass) can achieve, it was natural to assume (and Einstein's 1905 special relativity *predicted it* [8]) that a particle would offer an *increasing resistance* when accelerated to velocities approaching that of light. That is, a particle's mass will increase and will approach infinity when the particle's velocity approaches c, thus preventing it from reaching c.

This increase of mass with velocity has been repeatedly confirmed by experiments designed to test Einstein's prediction[7] and continuously (on a daily basis) confirmed by particle accelerators. Feynman specifically discussed the experimental confirmation of the velocity dependence of mass by particle accelerators:

[4] The measure of that resistance is the particle's mass.

[5] The measure of that increasing resistance is the particle's relativistic (velocity dependent) mass.

[6] Eq. 15.10 reads $\mathbf{p} = m\mathbf{v} = m_0\mathbf{v}/\sqrt{1 - v^2/c^2}$.

[7] Before the advent of special relativity the velocity dependence of mass had been predicted by Lorentz' electron theory, but Einstein demonstrated that the relativistic increase of mass applies to all matter.

> To deflect the high-speed electrons in the synchrotron that is used here at Caltech, we need a magnetic field that is 2000 times stronger than would be expected on the basis of Newton's laws. In other words, the mass of the electrons in the synchrotron is 2000 times as great as their normal mass, and is as great as that of a proton!

Again, Feynman did not state it explicitly, but his explanation is clear – a 2000 times stronger magnetic field is needed because high-speed electrons offer 2000 times *greater resistance* to their acceleration than slowly moving electrons; that is why the mass of high-speed electrons is 2000 times greater than the mass of slowly moving electrons.

As particle accelerators unambiguously demonstrate that the concept of relativistic mass reflects an experimental fact, the rejection of this concept amounts to rejection of the experimental evidence.

Even before the accelerators, the early experiments to test the prediction of Einstein's 1905 paper that the mass of a particle depends on its velocity *conclusively* confirmed it. The velocity dependence of the electron mass was confirmed in 1908 by Bucherer [9] and in 1916 by Guye and Lavanchy [10]. The proton relativistic mass variation was confirmed in 1958 [11].

Bucherer measured the ratio of charge to mass (e/m) for β-ray electrons and showed that at high velocities, comparable to the velocity of light, the masses of the electrons depended on their velocities. This experiment allowed *only* two interpretations – that either e or m varies in the ratio e/m – and independent experiments (see [12]) ruled out the interpretation that the electron charge decreases as its velocity increases. Therefore, the Bucherer experiment would be *impossible* if the mass of electrons did not increase as their velocities increase. That is why, rejection of the relativistic increase of the electron mass means rejection of Bucherer's experimental result.

The crushing experimental evidence that mass increases with velocity makes the rejection of this experimental fact truly inexplicable. Moreover, those who reject the concept of relativistic mass made, effectively, only two somewhat relevant objections against this concept.

A. The name "mass" cannot apply to both the magnitude of the four-momentum p (proportional to the rest mass m_0: $|p| = m_0c$), which is an invariant, and to the time component of the same four-vector (proportional to the relativistic mass m: $p^0 = m_0c/\sqrt{1 - v^2/c^2} = mc$) [13].

By the same logic, however, the name "time" should not apply to both the magnitude of the displacement four-vector Δx, between two events on a timelike worldline, (proportional to the proper time τ: $|\Delta x| = c\Delta\tau$), which is an invariant, and to the time component of the same four-vector (proportional to the coordinate time t: $\Delta x^0 = c\Delta t$) [14].

Therefore, if the concept of relativistic mass is rejected, by the same argument the name "time" should not be applied to the coordinate time and one should use only proper time. However, it is the coordinate time that changes relativistically – the experimentally tested time dilation involves precisely coordinate time.

Thus, rest or proper mass (which is an invariant) and relativistic mass (which is frame-dependent) are exactly like proper time (which is an invariant) and coordinate or relativistic time (which is frame-dependent).

B. The relativistic factor $\gamma = 1/\sqrt{1 - v^2/c^2}$ should not be "attached" to the mass of a particle since it "comes" from the particle's four-velocity. That γ "comes" from the particle's four-velocity is correct [14] – γ ensures that the velocity of a particle cannot reach and exceed that of light; in other words, γ ensures that no four-velocity vector, which represents the state of motion of a particle of non-zero rest mass, can become lightlike or spacelike. But that is kinematics; it says nothing about dynamics, that is, it says nothing about (i) *why* a particle cannot reach (and exceed) the velocity of light (i.e. *why* the particle's four-velocity cannot become lightlike or spacelike), and (ii) particularly, what is the mechanism, which prevents it from doing so? It is the concept of relativistic mass that addresses these questions.

In conclusion, both mass and relativistic mass are equally supported by the experimental evidence – since mass is defined as the measure of the resistance a particle offers to its acceleration (which is the accepted definition based on the experimental evidence) and since it is also an experimental fact that a particle's resistance to its acceleration increases as the particle's velocity increases, it follows that relativistic mass also reflects an experimental fact. This situation demonstrates that the rejection of the relativistic velocity dependence of mass amounts not only to rejections of experimental facts, but also to refusing to face and deal with a profound open question in fundamental physics – the origin and nature of the (inertial) resistance a particle offers when accelerated (an open question in classical physics) and of the increasing (inertial) resistance a particle offers when accelerated to velocities approaching that of light (an open question in spacetime physics). What makes this open question even more intriguing is that relativistic mass appears to behave as a tensor because a particle's resistance to its acceleration is *different* in different directions;[8] it is greatest along the particle's velocity (preventing it from reaching the velocity of light).

References

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