Matter without mass:  
do we really need the concept of mass?  

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Abstract

Einstein’s most famous equation – $E = mc^2$ – generated a short-circuit between the concepts of mass and energy, which also affects other concepts like matter, radiation, and vacuum. Physics currently has a mixture of classical, relativistic, and quantum concepts of mass, which generates a great deal of confusion and many problems. Clear definitions need to be established if one wants to avoid ghost hunting. In particular, by abandoning the idea of mass and focusing on time and energy, some interesting implications are emerging. It is noted that the cutoff frequency of the quantum vacuum energy, consistent with the observations of the cosmological constant, corresponds to that of the Cosmic Microwave Background. This might be consistent with the hypothesis of a rotating and expanding universe described by a Kerr-de Sitter metric with the observed cosmological constant. To verify this hypothesis is crucial to prove the rotation of the universe.

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1 Introduction

Mass is still one of the fundamental concepts of physics. Its definition developed and changed over the centuries, from Newton (quantity of matter in a

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given volume) to Einstein (measure of the energy content of a physical body), with random outbursts of debates such as the renormalization in quantum electrodynamics, the relativistic mass, and the genesis of the mass via the Higgs boson (see [8, 26] for detailed and pleasant reviews). These debates were never truly solved, but simply bypassed. Yet, it is still possible to see different mass concepts mixed together in different research fields. Perhaps, it is time to face with this problem again and to adopt a radical solution: the definitive removal of the concept of mass, at least from frontier physics.

At first glance, particle physicists already did it by adopting natural units, so that every quantity is in energy units. This choice is justified, as noted by the French philosopher Gaston Bachelard [7], by the fact that a physical particle is a real Kant’s *noumenon*, an unaccessible physical reality, but with hints of it emerging from experiments. The particle of modern physics is not a microscopic version of a human-sized object, like a ball or a spinning top. The size of a particle is determined in a dynamical way, as it depends on its cross section for collision with other particles. It has no geometrical size, but it has a temporal size determined by its energy. Space derives from the relationships between these particles, which are nothing more than knots of energy. These ideas recall somehow the thought by Fotini Markopoulou [30], with time/energy as fundamental quantities and the space emerging from relationships between objects.

However, these are only calculations tricks. Each research field has its own set of natural units, which in turn generates different results. Particle physicists adopt $\hbar = c = 1$, while astrophysicists and cosmologists use $G = c = 1$. A mass is expressed in terms of energy for the former, but as a length for the latter. Sometimes, the choice to set some constants – and not others – equal to one just depends on the personal taste of the individual researcher. This obviously generates confusion, and, most important, the idea of mass still lingers around. The very concept of particle is hinged on the concept of mass. If one thinks about excitations of a quantum field, the concept of mass is clearly at odds. The removal of the concept of mass requires also some changes in our way of thinking, particularly to draw more attention on time and energy.

\[\text{1 There is no need to abandon it in classical physics, where it still makes sense.}\]

\[\text{2 As commonly adopted, } \hbar = h/2\pi \text{ is the Planck constant, } c \text{ is the speed of light in vacuum, } G \text{ is the gravitational constant.}\]
2 Relativistic mass

One might think that it is useless to dig up again the old debate on the relativistic mass (e.g. [1, 11, 13, 19, 22, 29, 32, 34, 38, 41, 47]), but sometimes rehashing a little bit the basic equations can lead to interesting ideas. That debate showed that the so-called relativistic mass, composed of the rest (inert) plus the kinetic mass, was a misleading concept. The correct explanation is that the kinetic term is due to a change of the rhythm of time. If the time used to measure the velocity is the proper time, the definition of impulse remains unchanged (in textbooks – e.g. [17, 28, 36] – both explanations are presented; see also the interesting presentation in [44]).

Focusing on time, and its change of rhythm due to gravitation, should make it easier to understand the peculiar role of the photon. It has no rest mass, but it has impulse and energy. When passing through a gravitational field, which is nothing else than a significant concentration of energy, it simply changes its rhythm of time (red-/blue-shift of frequency) depending on the position in the gravitational field and its direction of motion. The photon, as a massless particle, can be thought as a universal clock\(^3\), if one is ready to abandon the assumption of uniformity and constancy of the rhythm of time. William Unruh wrote that “gravity is the unequable flow of time from place to place” rather than being the cause of a change of the rhythm of time [43]. However, this implies that time and energy are the same. Energy is what is needed to translate in time, but it is not time.

3 Newtonian mass

What can we say about the Newtonian, rest, inert mass? This an important question, because it sets also a boundary between matter and radiation. Newton’s definition was clearly based on macroscopic objects. In classical physics, the mass is the quantity of matter (solid, liquid, or gaseous) in a given volume, while the radiation is the electromagnetic field. All is easy.

Quantum mechanics showed us that solid, liquid or gaseous physical bodies are composed of molecules and atoms, which in turn are made of quarks and leptons. Electromagnetic and strong nuclear interactions bind these particles. However, both particles and bounds are energy. Once again, if one

\(^3\)Since the photon has no rest energy, there is no rest frame, and then no proper or comoving time. Really, no one can stop the flowing of time.
does not think about particles, but about quantum excitations of fields, it is immediately clear the role of energy.

The difference of matter with respect to radiation is the rest energy. Matter has energy even if it is at rest in some reference frame. A tiny part of this energy is necessary just to translate in time, just to exist at rest (existence energy\textsuperscript{4}, see \cite{23}). Most of energy is divided into bounds between particles, either molecular or subatomic bounds, and can be partially released by radioactive decay, or by breaking molecular or nuclear bounds. It is just a problem of different types of energy, condensed in different ways. Therefore, again, the concept of mass is no more necessary.

To summarize, matter is an aggregate of different types of energy, and one part is spent to exist at rest. Radiation is pure temporal energy, it is a universal clock, it cannot exist at rest, because it would be in contradiction with the concept of time. It is interesting to note that in the Standard Model, only two bosons are massless, the photon and the gluon. Both are responsible for generating bounds between particles, but the photon is more important because it can be used as a clock, while the very short range of the strong force makes the gluon useless for such a purpose (also the self-interaction of this boson hampers the possibility to serve as clock).

Before concluding this section, it is worth spending some words on the dark matter. In 1930s, Fritz Zwicky first speculated the existence of a non-luminous, non-baryonic matter by observing the radial velocities of galaxies in clusters. Later, Vera Rubin reported anomalous rotation curves of galaxies. Again, the mainstream explanation was searched in some exotic and unknown particle (see \cite{39} for a recent review), but despite decades of experiments, no detection was ever reported (e.g. see \cite{6} for one of the latest experimental reports). On the opposite, the searching for other explanations scored important discoveries. By using the superior astrometry of the \textit{Gaia} satellite, Crosta et al. \cite{18} showed that the rotation curve of the Milky Way can be explained by the contribution to the gravitational field of an off-diagonal term in the metric (due to rotation), without any need to invoke some exotic matter. MOND theory was instead successfully adopted to

\textsuperscript{4}Curiosity: the word atom derived from Greek \textit{a-tomos}, where the prefix \textit{a-} stands for not, while \textit{tomè} (cut) derived from \textit{tēmnein}, to cut. An atom would be something that cannot be cut. The word time has the same root, \textit{tem-nô}, and means to cut (see \cite{23} for an extended etymological analysis.). Therefore, the atom, the basic constituent of the matter, is not something that cannot be broken – as commonly thought – but it is something not subject to the cut of time.
explain the rotation curves of a sample of galaxies [16].

Particularly intriguing is the Crosta’s result [18], because one might think to search for a similar effect on cosmological scales. To test this hypothesis is necessary to prove the rotation of the Universe. Gödel [25] showed that a rotating universe would have an anisotropic distribution of galaxies, with an excess in one hemisphere. An attempt in this direction has been done by using the quasar catalog of the *Wide-field Infrared Survey Explorer* (*WISE*) satellite. A significant anisotropy, different from that of the CMB both in amplitude and direction (\(\sim 28^\circ\) difference), was found [40]. However, the main problem in this survey is that the extragalactic nature of the sources was inferred from magnitudes (photometric redshifts, color diagrams), not from spectroscopic observations. These methods are known to be not reliable, particularly for rapidly variable active galactic nuclei. Presently, no all-sky optical spectroscopic survey was ever done. The most recent one, the *Sloan Digital Sky Survey* DR14 Quasar Catalog [33], contains 526356 quasars with \(0.9 < z < 2.2\) distributed over 9376 square degrees (\(\sim 23\%\) of the sky), almost all on the Northern equatorial hemisphere (declination greater than \(-17^\circ\)). This is clearly not enough. A satellite with optical spectroscopic instruments is necessary to perform an all-sky spectroscopic survey (and, surely, the data of such a satellite will not be useful only for this test!). However, if most people keep looking for exotic particles, they will build nuclear detectors instead of telescopes and satellites.

4 Vacuum

The vacuum is the stone guest\(^5\): what can we say about the vacuum? Does it need of existence energy? If yes, then it would fall into the matter category. If it is pure temporal energy, then it would be radiation. If the space-time is quantized, then the vacuum could be the bound state of these quanta. But, again, it would fall into the matter category (in addition, one should also ask what might be the corresponding boson for this bound state). In addition, also matter contains vacuum: a solid body is made of atoms forming a crystal lattice, but most of space of the macroscopic physical body is vacuum. If

\(^{5}\)This must not be confused with the dipole anisotropy of the Cosmic Microwave Background (CMB) due to the motion of the Solar System, the Milky Way, and the Local Group [42, 21].

\(^{6}\)From the Molière’s play, *Don Juan or the Feast of Stone* (1665).
the vacuum is the bound state of quantized space-time, then would it be a compact aggregate or is there anything else?

If these considerations might seem specious and sophistic, I would like to remind the importance to understand what the stress-energy tensor in the Einstein’s field equations is representing. As Einstein himself wrote [20]:

“We make the distinction hereafter between gravitational field and matter in this way, that we denote everything but the gravitational field as matter. Our use of the word therefore includes not only matter in the ordinary sense, but the electromagnetic field as well.

Therefore, Einstein collected both matter and radiation under the word matter. If one thinks in terms of energy, this is a clear and justified choice, at least at a first order, having not included the energy of the gravitational field. If one thinks in terms of mass, then why putting together matter (mass) and radiation (massless)?

Einstein then added – and later deleted – the cosmological constant \( \Lambda \), which in turn is today confirmed by the observed tension in the Hubble constant [35]. However, calculations do not make sense and many hypotheses have been suggested (e.g. [46, 37, 9, 10, 14, 15, 12]). According to some authors \( \Lambda \) might be a zero-point curvature, an intrinsic property of space-time [9, 10], others suggested the existence of an exotic fluid, which generates negative pressure when interacting with baryonic matter [14, 15], but most researchers explain the constant as the effect of a dark energy, identified as the quantum vacuum energy. However, the observed value is different from the expected one by more than one hundred orders of magnitude [46, 37, 5, 12].

Also in this case, some notes are worth writing. Current quantum gravity theories are linked to the Planck units, which are physical quantities as functions of universal constants only (see [27] for a detailed review). Current theories should break down at the Planck energy \( E_P \), where space-time should be quantized:

\[
E_P = \sqrt{\frac{\hbar c^5}{G}} \sim 1.9 \times 10^9 \text{ J} = 1.2 \times 10^{19} \text{ GeV}
\]  

which is equivalent to a mass of \( \sim 2.2 \times 10^{-8} \) kg. When calculating the quantum vacuum energy, one takes into account the zero-point energies of the electromagnetic field (fermions fields have opposite fields and would
result in a vacuum with positive pressure) with a cut-off at Planck scale (e.g. [5]). Just to write down some order-of-magnitude calculation, the zero-point energy density $\rho_{\text{vac}}$ in the frequency range $[\omega_1, \omega_2]$ is [31]:

$$\rho_{\text{vac}} = \int_{\omega_1}^{\omega_2} \frac{\hbar \omega^3}{2\pi^2 c^3} d\omega = \frac{\hbar}{8\pi^2 c^3} (\omega_2^4 - \omega_1^4) = \frac{\hbar \pi}{c^3} (\nu_2^4 - \nu_1^4)$$  \hspace{1cm} (2)

where $\omega = 2\pi \nu$. The Planck frequency is:

$$\nu_P = \frac{E_P}{\hbar} = t_P^{-1} = \sqrt{\frac{c^5}{\hbar G}} \sim 1.8 \times 10^{43} \text{ Hz}$$  \hspace{1cm} (3)

Therefore, by taking $\nu_1 = 0$ and $\nu_2 = \nu_P$, it results $\rho_{\text{vac}} \sim 8 \times 10^{115} \text{ erg/cm}^3$. This value must be compared with that observed on cosmological scale: $\rho_\Lambda \sim 4 \times 10^{-9} \text{ erg/cm}^3$ [3]. The difference is crystal clear.

If one forgets about the quantization of space-time and simply adopts the observed value $\rho_\Lambda$ to set a constraint on the cut-off frequency, then rearranging Eq. (2) and setting $\rho_{\text{vac}} = \rho_\Lambda$, one obtains:

$$\nu_{\text{cut}} = 4 \sqrt{\rho_\Lambda c^5} \hbar \pi \sim 1.5 \times 10^{12} \text{ Hz}$$  \hspace{1cm} (4)

Interestingly, the peak frequency of the spectral radiance of the Cosmic Microwave Background (CMB) is $(1.6 - 2.8) \times 10^{11} \text{ Hz}$, so the two values are consistent within one order of magnitude. Given all the approximations adopted, this is a really intriguing result. If these frequencies are really correlated, and not by a chance coincidence, what might be the implications? The first one is that the vacuum is not related to the quanta of space-time identified with the Planck scale. If the generation of the vacuum as zero-point energy of the electromagnetic field is related to the epoch of CMB, it might imply the need of the photon decoupling and the availability of photons free to fill in all the Universe. The CMB would not only be the last scattering surface, but also be the dark energy horizon. The vacuum is therefore not the absence of matter and radiation, but it is the zero-point energy of the radiation permeating the universe. Being photons the universal clocks, their zero-point energy might be a sort of calibration energy, a further proof of the direction of time: no photons with negative energy are available.

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7 It should be noted that the Planck scale has no physical reason. It is just a play with some fundamental constants. Therefore, if a quantization of space-time will be realized, it might also be completely detached from the Planck scale.
no backward clocks can be found in nature. The vacuum energy must be
the same everywhere, otherwise there could be local domains in the universe
where it might be possible to have negative energies, and hence backward
clocks.

To search for similar horizon effects on local nearby scales, one might
think at astrophysical black holes. The generally adopted Kerr metric can
be transformed into a Kerr-deSitter space-time by adding a dark energy
constant $\Lambda$ [2] (the two metrics are coincident for $\Lambda = 0$). The presence of
dark energy in the latter metric implies one more horizon in addition to the
gravitational radius. The problem is that with the current observed value of
$\Lambda \sim 2 \times 10^{-56}$ cm$^{-2}$ is too small to generate the additional horizon on local
scale. By using the example proposed by [2] and one of the most massive
black hole known (S5 0014 + 813, $z = 3.366$, $M \sim 4 \times 10^{10} M_\odot$ [24]), it
results that to obtain an observable dark energy horizon of $r_{\text{deh}} \sim 4 \times r_g \sim
2.4 \times 10^{16}$ cm, it would be necessary $\Lambda \sim 3 \times 10^{-33}$ cm$^{-2}$, about 23 orders
of magnitude greater than the known cosmological $\Lambda$. In addition, decades
of observations never shown significant and anomalous deviations from the
Kerr metric.

However, if this does not work on local scales, it is interesting to apply
the above cited Kerr-deSitter metric to the early universe. As stated above,
the CMB might also be the dark energy horizon and one might think it could
be the additional horizon of the initial space-time singularity, generated by
the presence of dark energy. At the epoch of CMB ($z \sim 1100$), the comoving
radial distance was $\sim 4.3 \times 10^{28}$ cm (by adopting the cosmological parameters
measured by the Planck Collaboration [3]). By assuming $r_{\text{deh}}$ equal to this
value, with the example proposed by [2], it results that $\Lambda \sim 10^{-57}$ cm$^{-2}$
and the energy of the singularity is estimated to be $8 \times 10^{79}$ GeV. The
implications are twofold: on one side, it confirms that the CMB epoch might
be the horizon for dark energy, but on the other side, it suggests an almost
maximally rotating universe. The observational proof of a rotating universe,
suggested in the previous section, has now one more reason to be done.

5 Energy

Focusing on time, and hence on energy, opens interesting research directions.
As noted in my previous work [23], matter does need of an existence energy,
the minimum to exist at rest, just to travel in time. The key experiment is
to measure the lifetime of protons and electrons, which is currently just a lower bound (e.g. [4]). A measured value will also allow us to set a constraint on the lifetime of the universe, if any. Further questions might be how and where this energy is dissipated: is it simply lost? Or is it converted? In the first case, this clearly violates the principle of energy conservation, which was already challenged on cosmological scales, given the arrow of the expansion of the universe (see [45] for a recent review; see also the interesting thread on Twitter by William H. Kinney). If the existence energy is converted, then the energy conservation might be saved, but what other form of energy is the result of this conversion?

6 Conclusions

I wanted to show how new research directions are emerging just by abandoning the mass-particle paradigm. Instead of searching for new exotic particles or unnecessary quantizations, one might explore new space-time metrics, new types of energy, changes in the rhythm of time. The current mixture of classical and frontier concepts, that is keeping us bound to the concept of mass, might be lethal for physics in the long term, while focusing on time and energy opens new, and intriguing research lines.

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