The rocket equations for decays of elementary particles

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Abstract

The decay of elementary particles is described nonrelativistically and using the method of the special theory of relativity. Then the Tsiolkovskii rocket equation is applied to the one photon decay of the excited nucleus of the Mössbauer effect. The formation time of photons during decay is supposed nonzero. The Meščerskii equation is possible to identify with the bremsstrahlung equation. All decays described in the “Review of Particle physics properties” can be investigated from the viewpoint of the rocket equations

Key words. Classical decay of a particle, the Tsiolkovskii rocket equation, the Meščerskii equation, Mössbauer effect, excited electron, the bremsstrahlung equation.

1 Introduction

Many elementary particles are not stable and can decay to the different components as it is shown in “Review of Particle physics properties” (Alvarez-Gaumé, 2004). To be pedagogically clear we first describe the classical decay of particles. We follow the text of Landau et al. (Landau et al. 1965), where the decay of elementary particles is described nonrelativistically and using the methods of the special theory of relativity (Landau et al. 1962). The quantum field theory describes decays of elementary particles only using the asymptotic states. Decay is stimulated (under the influence of the external forces), or, spontaneous (under the influence of internal forces, or hidden external forces). The most simple description of decay is in the system where the original particle was in the state of rest. With regard to the validity of the momentum conservation law, the particles have the same magnitude of the momentum, however they moves in the opposite direction.

If the decay is photonic, then we suppose that the Tsiolkovskii rocket equation can be applied to the one photon decay of the excited nucleus. First, we apply it to the the
Mössbauer process. The formation time of photons during decay is supposed nonzero as an analog to the Einstein idea (Einstein, 1926). If electron is accelerated then it radiates. We show the Meščerskii equation is possible to identify with the bremsstrahlung equation where electron is in the permanent decay. Many other decays can be investigated from the view point of the Meščerskii equations. We think that the decays described in the “Review of Particle physics properties” (Alvarez-Gaumé, 2004) can be investigated from the viewpoint of the rocket equations. The article is the original trial to unify the cosmonautic physics with particle physics.

2 The decay of the nonrelativistic particles

Let as consider a decay of some particle to two particles 1 and 2. The most simple is to consider the decay in the rest system of the original particle. The conservation law of momentum is valid during the decay and it means that particles are emitted with the same momenta in the opposite directions. Let us denote the magnitude of the momentum of every particle as \( p_0 \). Then the energy conservation laws reads:

\[
E_{\text{int}} = E_{1\text{int}} + \frac{p_0}{2m_1} + E_{2\text{int}} + \frac{p_0}{2m_2},
\]

(1)

where \( m_1, m_2 \) are particle masses and \( E_{1\text{int}}, E_{2\text{int}} \) are their internal energies and \( E_{\text{int}} \) is the internal energy of the original decaying particle. If \( \varepsilon \) is the energy of the decay, then evidently

\[
\varepsilon = E_{\text{int}} - E_{1\text{int}} - E_{2\text{int}}
\]

(2)

and this energy must be positive in order to be the decay possible.

It follows from eq. (2) and (1) that

\[
\varepsilon = \frac{p_0^2}{2} \left( \frac{1}{m_1} + \frac{1}{m_2} \right) = \frac{p_0^2}{2m}.
\]

(3)

where \( m \) is the reduced mass of both particles. The velocities of every particle are \( v_{10} = \frac{p_0}{m_1} \) and \( v_{20} = \frac{p_0}{m_2} \).

Now, let us consider the so called the laboratory system \( L \) where the the original particle moves with the velocity of the magnitude \( V \). Let us consider one of the particle and denote its velocity as \( \mathbf{v} \) in the \( L \)-system and \( \mathbf{v}_0 \) in the CMS. Then,

\[
\mathbf{v} = \mathbf{V} + \mathbf{v}_0, \quad \text{or} \quad \mathbf{v} - \mathbf{V} = \mathbf{v}_0
\]

(4)

and

\[
v^2 + V^2 - 2vV \cos \theta = v_{0}^2,
\]

(5)

where \( \theta \) is the angle of escape of the particle with regard to the direction of the velocity \( \mathbf{V} \).

If the angle of escape of the particle in the CMS system is \( \theta_0 \), then there is an elementary relation between \( \theta \) and \( \theta_0 \). Or, (Landau et al., 1965):

\[
\tan \theta = \frac{v_0 \sin \theta_0}{v_0 \cos \theta_0 + V}.
\]

(6)
If we solve this equation in order to get \( \cos \theta_0 \), the we obtain after some elementary operations (Landau et al., 1965):

\[
\cos \theta_0 = -\frac{V}{v_0} \sin^2 \theta \pm \cos \theta \sqrt{1 - \frac{v^2}{v_0^2} \sin^2 \theta}.
\] (7)

If the decay angles are \( \theta_1 \) and \( \theta_2 \) in the L-system, then there is the following relation between \( \theta_1 \) and \( \theta_2 \) (Landau et al., 1965):

\[
\frac{m_2}{m_1} \sin^2 \theta_2 + \frac{m_1}{m_2} \sin^2 \theta_1 - 2 \sin \theta_1 \sin \theta_2 \cos(\theta_1 + \theta_2) = \frac{2\varepsilon}{(m_1 + m_2)V^2} \sin^2(\theta_1 + \theta_2). \]

(8)

3 The decay of the relativistic particles

Let us consider, following Landau et al. (1962) the relativistic spontaneous decay of a body of mass \( M \) into two particles with mass \( m_1 \) and \( m_2 \). Let us consider the decay in the system where the body is at rest. The law of the conservation of the relativistic energy is

\[
M = E_{10} + E_{20},
\]

(9)

where \( E_{10} \) and \( E_{20} \) are the relativistic energies of the emerging particles. Here the velocity of light is \( c = 1 \). Since \( E_{10} > m_1 \) and \( E_{20} > m_2 \), the equality (9) can be satisfied only when \( M > m_1 + m_2 \), i.e. a particle can disintegrate spontaneously into two parts when the sum of their masses is less than the mass of the original particle. On the other hand, when \( M < m_1 + m_2 \), the original particle is stable and does not decay spontaneously. To cause the decay in this case, we must to supply to the original particle some energy from outside. The applied energy must be at least the binding energy \( m_1 + m_2 - M \).

The momentum must be also conserved in the decay process. Since the initial momentum of the original particle was zero, the sum of the momenta of the emerging particles must be also zero, or \( \mathbf{P}_{10} + \mathbf{P}_{20} = 0 \). Consequently \( p_{10}^2 = p_{20}^2 \), or

\[
E_{10}^2 - m_1^2 = E_{20}^2 - m_2^2.
\]

(10)

The to equations (9) and (10) uniquely determine the energies of the emerging particles:

\[
E_{10} = \frac{M^2 + m_1^2 - m_2^2}{2M}, \quad E_{20} = \frac{M^2 - m_1^2 + m_2^2}{2M}.
\]

(11)

Now, let us suppose that the original particle is moving with the velocity \( V \) and dissociates “in flight” into two particles with mass \( m \). Let us determine the relation between angle of emergence of these particles and their energies. Let be \( E_0 \) the energy of one particle in the CM-system. In other words the energy is given by the formula (11). If \( \theta \) is the angle of the emergence in the L-system, then using the relativistic transformation formulas, we get (Landau et al., 1962):

\[
E_0 = \frac{E - V p \cos \theta}{\sqrt{1 - V^2}},
\]

(12)

from which follows

\[
\cos \theta = \frac{E - E_0 \sqrt{1 - V^2}}{V \sqrt{E^2 - m^2}}.
\]

(13)
For determination of $E$ from $\cos \theta$ we then get the quadratic equation.

$$E^2(1 - V^2 \cos^2 \theta) - 2E E_0 \sqrt{1 - V^2} + E_0^2(1 - V^2) + V^2 m^2 \cos^2 \theta = 0,$$

which has one positive root (if the velocity $v_0$ of the decay particle in the CM-system satisfies $v_0 > V$), or two positive roots if $v_0 < V$. The more detailed discussion of this case is described in Landau et al. (1962) textbook.

Now, let us consider the situation where the particle with mass $M$ in rest decays into the system of the three particles $m_1, m_2, m_3$. Let us answer the question, what is the maximal energy of particle $m_1$ of the three-body system.

The solution of this problem is as follows (Landau et al. 1962). The particle $m_1$ has its maximum energy if the system of the other two particles $m_2, m_3$, is the least possible mass which is the sum $m_2 + m_3$ and corresponds to the case where the rest particles moves together with the same velocity. So, we can reduce the problem to the decay of a body into two parts, and so we get using eq. (11) the following expression (Landau et al. 1962):

$$E_{1,\text{max}} = \frac{M^2 + m_1^2 - (m_2 + m_3)^2}{2M}.$$

4 The Tsiolkovskii rocket equation for decay

There are some experiments which prove the particle properties of a photon. On the other hand photon moves as a wave with the wave length $\lambda$ and moves with velocity $c$ in vacuum. The particle-wave synthesis can be expressed by the relation $p = \hbar \omega / c$ where $p$ is a momentum of the photon and $\omega$ is its frequency. The mass of photon follows from the Einstein energetic relation $E = mc^2$ as $m = \hbar \omega / c^2$.

However, when an excited nucleus $N^*$, (for instance of the Mössbauer effect) decays according to the equation $N^* \rightarrow N + \gamma$, then during the very short interval photon is created and it has no particle and wave properties. The problem of the process of emission of photon was firstly formulated by Einstein (1926). He tried to decide if photon is created at one moment, or as a wave during some formation time. This Einstein work has continuation in the the blackbody article where Einstein supposes only the quanta of electromagnetic energy, later denoted by photons, but he does not consider the formation time of photons. (Einstein, 1917). From the Einstein period, photon is the most mysterious particle in universe.

We here suppose that there is a formation time of a photon and it can be evidently postulated as $T = \lambda / c$ as the minimal time for the formation of the wave length $\lambda$. During the formation time the nucleus $N$ is accelerated according to the equation $v = at$, where $a$ is acceleration and the final velocity $v_f$ is $v_f = a\lambda / c$. The velocity of the nucleus during the formation time of photon must be described by the rocket equation by Tsiolkovskii (1962):

$$v = c \ln \left( \frac{m_0}{m(t)} \right),$$

where $c$ is the velocity of light and it is the velocity of the light as the medium, $m_0$ is the initial mass of the nucleus and $m(t)$ is the variable mass during the formation of a photon. The nucleus is micro-rocket during the formation time of photon.

In the formation time $T = \lambda / c$ we can write
\[ m = m_0 - m_0 \alpha t = m_0(1 - \alpha t) \approx m_0 e^{-\alpha t}; \quad 0 < t < \lambda / c. \quad (17) \]

Then, from equation (16) and (17) it follows that

\[ v = c \alpha t. \quad (18) \]

We have for the acceleration \( dv/dt = a = c \alpha = v_f / T, \) where

\[ v_f = \frac{\hbar \omega}{m_0 c}. \quad (19) \]

Then it easily follows that

\[ \alpha = \frac{1}{2 \pi} \frac{\hbar \omega^2}{m_0 c^2}. \quad (20) \]

and then

\[ m(t) = m_0 e^{-\frac{1}{2 \pi} \frac{\hbar \omega^2 t}{m_0 c^2}}; \quad 0 \leq t \leq \lambda / c. \quad (21) \]

In case that the mass of crystal in the Mössbauer experiment is \( M_0 \) and the time dependence of mass of crystal is \( M(t) \) and the recoil is transmitted to the crystal as a whole, then instead of eq. (21) we write:

\[ M(t) = M_0 e^{-\frac{1}{2 \pi} \frac{\hbar \omega^2 t}{M_0 c^2}}; \quad 0 \leq t \leq \lambda / c. \quad (22) \]

So we have seen that the combination of the elementary relativity equations with the Tsiolkovskii rocket equation, the decay of nucleus is described during the formation time of photon. It also means that the Mössbauer effect can be completed by the information on the microscopical description of the decay of nucleus. In case that the mass of the decaying object is the whole crystal as it is supposed in case of the low temperature Mössbauer situation, then, the mass change of the crystal is practically zero. The quantum mechanical probability that the crystal survive at the zero temperature at the same state after emission of the photon with momentum \( P \) is

\[ Probability = \exp \left\{ -\frac{P^2}{\hbar^2 \langle Z_M^2 \rangle} \right\}, \quad (23) \]

where \( \langle Z_M^2 \rangle \) is the average shift of the emitting nucleus from the equilibrium position (Feynman, 1972). The analogous expression is valid for the finite-temperature Mössbauer effect.

5 The Meščerskii rocket equation

Let us consider the nucleus with mass \( m \) moving with the velocity \( \mathbf{v} \) with regard to the inertial system \( S \) at time \( t \) and the force \( d\mathbf{F} \) acts during the time \( dt \) on the nucleus and during this infinitesimal time the mass \( dm_1 \) is emitted with he velocity \( \mathbf{u}_1 \) and the mass \( dm_2 \) is emitted with he velocity \( \mathbf{u}_2 \). The equation of the infinitesimal motion of this system is as follows:

\[ d\mathbf{p} = d(m\mathbf{v}) = m d\mathbf{v} + \mathbf{v} dm = md\mathbf{v} + \mathbf{v}(dm_1 + dm_2) \quad (24) \]
At the same time, the following equation is correct:

\[ d(mv) = Fdt + u_1dm_1 + u_2dm_2, \quad (25) \]

which is the Newton law of action and reaction.

The equation (25) can be evidently written in the form

\[ \frac{dp}{dt} = F + u_1\frac{dm_1}{dt} + u_2\frac{dm_2}{dt}. \quad (26) \]

Then, we have from eqs. (24) and (26) the so called Meˇšcerskii rocket equation (Meˇšcerskii, 1962, Kosmodemiakskii, 1955, 1966):

\[ m\frac{dv}{dt} = F + (u_1 - v)\frac{dm_1}{dt} + (u_2 - v)\frac{dm_2}{dt}. \quad (27) \]

If we consider the emission of many masses \( dm_1, dm_2, ... dm_N \), then we get instead of of equation (27), the following equation

\[ m\frac{dv}{dt} = F + \sum_{i=1}^{N}(u_i - v)\frac{dm_i}{dt}. \quad (28) \]

In case that we consider only emission of one mass component and the zero force acting on the accelerated nucleus, then there is no mass term \( dm_2 \) an the motion is one-dimensional with the corresponding Tsiolkovskii equation:

\[ m\frac{dv}{dt} = v_r \frac{dm}{dt}. \quad (29) \]

where \( v_r \) is the relative velocity of the emitted mass with the regard to the nucleus.

The corresponding solution can be easily find as follows:

\[ v = v_0 + v_r \ln \frac{m_0}{m(t)}. \quad (30) \]

where \( m_0 \) is the initial mass of the nucleus and \( m(t) \) is its instantaneous mass at time \( t \).

The Tsiolkovskii equation in the gravitational field follows from eq. (29) evidently in the form

\[ m\frac{dv}{dt} = -mg + v_r \frac{dm}{dt}, \quad (31) \]

with the solution

\[ v = v_0 - gt + v_r \ln \frac{m_0}{m(t)}. \quad (32) \]

There are many nuclei which can be in the excited states and the decays, cannot be necessarily one-photon decay but multi-photon decay. \( N^* \rightarrow \gamma + \gamma + ... \gamma \).

In this case it is necessary to generalize the dependence of mass of nucleus on time. We can suppose that the decay starts at the same moment. Let us remark that the whole situation can be still generalized to the case with massive photon and to the multi-photon decay with the massive photons. Massive photons are physically meaningful as it is supposed in the author articles (Pardy, 2002, 2004).
6 Decay of accelerated electron and rocket equations

When electron (or every charged particle) is accelerated, then it radiates the electromagnetic energy. The nonrelativistic equation of motion involving the acceleration is as follows (Landau et al., 1988):

\[ m \ddot{\mathbf{v}} = \mathbf{F} + \frac{2e^2}{3c^3} \dot{v}. \]  

(33)

If we postulate the compatibility of the Meščerskii equation with the above equation, then, in the 1-dimensional case with \( c \gg v \), we get after comparison of the these equations:

\[ \frac{2e^2}{3c^3} \dot{v} = -c \frac{d\delta m}{dt}. \]  

(34)

from which follows the following dependence of emitted mass of the decaying electron (being accelerated):

\[ \delta m = -\frac{2e^2}{3c^4}a. \]  

(35)

The interpretation of the result is that accelerated electron (or the charged particle) is during the acceleration in the permanent excited state, or,

\[ e^* \rightarrow e + \gamma \]  

(36)

and the mass of the accelerated electron is renormalized according the equation

\[ m \rightarrow m + \delta m; \quad \delta m = -\frac{2e^2}{3c^4}a. \]  

(37)

for all time of acceleration. It means that electron moving in the magnetic field is in the permanent excited state which permanently decays. The mass of decay is obtained by the absorptive mechanism which was still not described in the classical textbooks on electromagnetism. The quantum version of the absorptive mechanism is also unknown. We think that the decay of the excited electron in the magnetic field is not the same as the decay of the high-energy excited electron investigated in the high-energy laboratories such as CERN.

7 Decay of \( K^+ \) meson

The decay of \( K^+ \)-meson (\( \theta \)-decay) is radiative with emission of the \( \gamma \)-photon, or nonradiative where the gamma-photon is not present. So the nonradiative decay is (We do not consider the \( \tau \)-decay expressed as \( K^+ \rightarrow \pi^+ + \pi^+ + \pi^- \), which is the substantial ingredient of the CPT theorem, which was not still investigated from the viewpoint of the rocket equations):

\[ K^+(p) \rightarrow \pi^+(q_1) + \pi^0(q_2) \]  

(38)

and the radiative decay is

\[ K^+(p) \rightarrow \pi^+(q_1) + \pi^0(q_2) + \gamma(k) \]  

(39)
The matrix element of the radiative decay of $K^+$-meson is (Efrosinin, 2006):

\[
\langle \pi^0, \pi^+, \gamma | S | K^+ \rangle = ie(2\pi)^4 \delta^4(q_1 + q_2 + k - p)\varepsilon^\mu M_\mu(k) \quad (40)
\]

where

\[
M_\mu(k) = M_\mu^{\text{photon emission from external line}}(k) + M_\mu^{\text{direct vector contribution}}(k) + M_\mu^{\text{direct axial contribution}}(k). \quad (41)
\]

Efrosinin (2006) show by calculation that the dominant contribution to the K-meson decay comes from the bremsstrahlung term.

However, because we suppose that the decay can have the different form which are not involved in the Feynman diagrams, we postulate the possibility the following modification of the K-meson decay:

\[
K^+(p) \rightarrow (\pi^+(q_1) + \pi^0(q_2)) + \gamma(k) \quad (42)
\]

and it means that this decay can be described by the rocket equations from which follows the exponential decline of mass of the system $(\pi^+(q_1) + \pi^0(q_2))$. Let us still remark that the system $(\pi^+(q_1) + \pi^0(q_2))$ as a bound system can be described by the quark formalism.

8 The alpha, electron, positron and neutrino decays

If the decay component is only gamma photons, then the decay is massless because the rest mass of photon is zero. There are many reactions which combine different types of decays (Rohlf, 1994). Let us write some examples, which can be also described by the quark formalism.

\[
^{12}C \rightarrow ^8Be + \alpha \quad (43)
\]

is massive decay because the $\alpha$-particle is massive one. Similarly

\[
^{12}C \rightarrow ^8Be + \alpha, \quad ^8Be \rightarrow \alpha + \alpha, \quad ^{210}Po \rightarrow ^{206}Po + \alpha \quad (44)
\]

are massive decay.

The combined decays are the following ones:

\[
^8Be \rightarrow ^8Be + e^+ + \nu_e \quad (45)
\]

and

\[
^{15}O \rightarrow ^{15}N + e^+ + \nu_e \quad (46)
\]

are massive decay in combination with massless decay because we suppose that neutrino is massless particle.

At present time it is not establish experimentally the process of decay of Beryllium and Oxygen. There is a possibility of the following equations of the decays:

\[
^{60}Co \rightarrow (^{60}Co + e^-) + \nu_e \quad (47)
\]
and

\[ ^{15}O \rightarrow (^{15}N + e^+) + \nu_e, \]  

which can be interpreted in such a way that the first step is the emission of neutrino and then the emission of positron. The experimental verification of such process can be performed with the inserting this process in the very strong magnetic field and then the process will be realized according to Meščerskii equation as follows:

\[ m \frac{dv}{dt} = \frac{q}{c} (v \times H) + \sum_{i=1}^{N} (u_i - v) \frac{dm_i}{dt}, \]  

where the external force of the equation (11) was replaced by the Lorentz force for the motion of a charged particle in an electromagnetic field. To our knowledge, such experiment was not still performed. This experiment can also be applied to the decay of $\mu^+$-meson, because the decay equation is as follows

\[ \mu^+ \rightarrow e^- + \nu_e + \bar{\nu}_e. \]  

Similarly, we can consider the decay of excited electron according to the equation $e^* \rightarrow e + \gamma$, which is of course massless decay. To our knowledge such decay was not confirmed in the particle laboratories.

The decay of neutron is a such that in reality neutron and proton have a rich substructure of quarks and gluons so that the $\beta$-decay diagrams are oversimplified. However, at the quark level, the process

\[ n \rightarrow p + e^- + \bar{\nu}_e \]  

\[ d \rightarrow u + e^- + \bar{\nu}_e \]  

can be considered as

i.e. d-quark changes via quark-weak coupling to u-quark, an electron and antineutrino. The decay (51) and (52) can evidently be considered from the viewpoint of the rocket equations.

At the same time the decay of the Higgs particle can be considered from the viewpoint of the rocket equations. The same is valid for the broken quark confinement. In the astrophysics, the nonsymmetrical supernova explosion from the viewpoint of the rocket equation was not investigated till the present time.

9 Discussion

We considered the decay of elementary particles nonrelativistically and using the method of the special theory of relativity. The asymptotic states of the quantum field theory was not considered. Then, the Tsiolkovskii rocket equation was applied to the one photon decay of the excited nuclei of the Mössbauer effect. The formation time of photons during decay was supposed to be nonzero. The Meščerskii equation was identified with the bremsstrahlung equation for electron in order to get that electron is in the permanent decay during acceleration for instance when moving in the electromagnetic field. Our theory concerns all decays described in the “Review of Particle physics properties” (Alvarez-Gaumé, 2004) and every decay can be investigated with regard to the rocket
equations. The rocket equations were still not used in the microphysics and in the nanophysics. However, they are not prohibited.

From the viewpoint of the rocket equation the mass of nucleus in the Mössbauer effect is exponentially formatted. Similarly the possible bound state of elementary particle is formatted exponentially. The question of application of this fact to some calculations in QCD is open. In QFT we use only asymptotic states, which means that the description of reality is incomplete. The theory of electroweak interaction must evidently work with the formation time of particle mass and formation time of photon. The formation time of photon was considered by Einstein (1926). The formation time of mass and formation time of photon is reality. There is no quantum process with the zero formation time.

How to confirm our theory by experiment? Careful observation of a single electron in an atom trap over a period of several months by Gabrielse at al. has resulted in the best measurement yet of the electron’s magnetic moment and an improved value for alpha, the fine structure constant. Why not use this method in the modified form for case where a charged particle radiates in the magnetic field, or in case of the Mössbauer process, or in case of decays of elementary particles?

Gerald Gabrielse and his students Brian Odom and David Hanneke at Harvard combined electric and magnetic forces to keep the electron in its circular "cyclotron" orbit. In addition to this planar motion, the electron wobbles up and down in the vertical direction, in the direction of the magnetic field (D’Urso et al., 2005).

The measured value of g can also be used to address the issue of hypothetical electron constituents. Such subcomponents could be no lighter than 130 GeV. On the basis of this experiment one can also place a corresponding limit on the size of the electron; it must be no larger than $10^{-18}$ m across. (Odom, et al. 2006).

We believe that the processes described in the above text and other processes of particle and nuclear physics can be experimentally confirmed by the modified Gabrielse et al. methods.

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