Research Article

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Effect of the gravitational field strength on the rate of chemical reactions

https://doi.org/10.1515/phys-2024-0062
received December 11, 2023; accepted June 19, 2024

Abstract: The magnitude of the rate of chemical reactions also depends on the position in the gravitational field where a chemical reaction is being carried out. The rate of chemical reaction conducted at a stronger gravitational field, *i.e.*, near the surface of some heavy planet, is slower than the rate of reaction conducted at a weaker gravitational field, *i.e.*, away from the surface of a heavy plant, provided temperature and pressure are kept constant at two positions in the gravitational field. The effect of gravity on the rates of reactions has been shown by formulating the rate constants from almost all types of reaction rate theories, *i.e.*, transition state theory, collision theory, Rice–Ramsperger–Kassel–Marcus, and Marcus's theory, in the language of the general theory of relativity. The gravitational transformation of the Boltzmann constant and the energy quantum levels of molecules have been developed quantum mechanically. A gravitational transformation of thermodynamic state functions has been formulated that successfully explains the quasi-equilibrium existing between reactants and the activated complex at different gravitational fields. Gravitational mass dilation has been developed, which explains that at weaker gravitational fields, the transition states possess more kinetic energy to sweep translation on the reaction coordinate, resulting in the faster conversion of reactants into products. The gravitational transformation of the half-life equation shows gravitational time dilation for the half-life period of chemical reactions and thus renders the general theory of relativity and the present theory in accord with each other.

Keywords: gravitational time dilation, energy spacing, chemical kinetics, gravitational Boltzmann constant, general theory of relativity

1 Introduction

The special theory of relativity proposed by Einstein appeared in 1905 [1,2] and discarded the absolute notions of space and time. General relativity was born because of efforts to extend the special theory of relativity to non-inertial frames [3]. It describes gravity as an effect rather than a force [4]. It completely interweaves space and time into one entity: space-time. This space-time behaves as a flexible fabric. Warps and curves in this fabric of space-time are the origin of gravity. The geometry of this four-dimensional space-time fabric completely defines the behavior of gravity. General relativity explains that clocks located near the surface of a heavy planet, *i.e.*, those with stronger gravitational potential, run slower than clocks located at a certain appreciable height from the surface of a planet, *i.e.*, those with weaker gravitational potential. Gravitational time dilation is a type of time dilation that describes an actual difference in elapsed time between two events as measured by observers situated at varying distances from a gravitating mass. The closer the clock is to the source of gravity, *i.e.*, at a stronger gravitational potential, the slower the time passes for it. Moving the same clock away from the source of gravitation, *i.e.*, at a weaker gravitational potential, speeds up its time flow [3]. This effect has also already been experimentally verified [5]. In the past, there have been few attempts to study the effect of gravity on chemical reactions [6,7], but a theory that can truly explain how gravity will really affect the rate of chemical reactions is missing so far. More than three decades before, Ohsumi also made an attempt to explain chemical reactions from the point of special and general relativity [8] but without taking into account relativistic and gravitational time dilation effects. Recently, one attempt has been made to study the effect of gravity on chemical reactions, but the claim of that study totally disagrees with that of general relativity [9]. Since general relativity explains that time slows down near the surface of heavy planets where gravity is strong, chemical processes should slow down near the source of gravitation, *i.e.*, at a stronger gravitational field [3]. However, Lecca has claimed that intense gravity will speed up rates of chemical reactions

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[9], which is opposite to the gravitational time dilation phenomenon [3]. Therefore, the present study is the first attempt to invoke gravitational time dilation in chemical kinetics that can explain the effect of gravity on the rates of chemical reactions in the gravitational potential of an arbitrary massive planet with mass M.

2 Theory

To compare the rates of chemical reactions at different positions in the gravitational field where gravity is stronger at positions closer to the surface of a heavy planet and weaker at appreciable heights from the surface of a planet, temperature and pressure at two positions should be kept the same, as rates of chemical reactions are affected by variations in temperature and pressure [10]. Since gravity is defined as an effect that emerges as an entropic force whose origin is explained by employing a canonical ensemble, it ensures that the temperature remains constant in the entire gravitational field [11]. Black hole thermodynamics [12,13] also supports the fact that temperature is not affected by the strength of the gravitational field. This is quite similar to the Lorentz invariance of temperature [14], which has been proven to be Lorentz-invariant using quantum statistical treatment centered on the zeroth law of thermodynamics [15] and phenomenological analysis [16]. The relativistic theory of chemical kinetics, which is the first attempt to explain relativistic time dilation in chemical and nuclear reactions [17], also fully supports Lorentz invariance of temperature. To explain gravitational time dilation, we first need to consider the relativistic increase in mass for observers moving at fractions of the speed of light. For a particle moving at a fraction of the speed of light, an increase in its mass will be given, which is defined as

$$m_\mathrm{u} = 1/\sqrt{1 - u^2/c^2}\, m_0. \tag{1}$$

When particles are moving at a sufficient, weaker speed, there is an increase in their mass. This relativistic mass for particles moving at weaker speeds is a consequence of the special theory of relativity [1–3]. To have compatibility between the special theory of relativity and general relativity, mass dilation for particles in a gravitational field should exist, like gravitational time dilation [3]. It can be developed considering a simple gedanken experiment. It is known that when a beam of photons is moved straight from a region of stronger gravitational potential (near the source of gravity) to a region of weaker gravitational potential (away from the source of gravity), it undergoes redshift, *i.e.*, its wavelength decreases at a weaker gravitational potential [18]. The gravitational attraction that leads to a general mass accretion of massive particles has already been reported [19]. Now consider a thought experiment in which either a beam of electrons or atoms is projected against gravitational potential (from a region of stronger gravitational potential to a region of weaker gravitational potential) due to a gravitational redshift. The de Broglie wavelength of either atoms or electrons will be greater at weaker gravitational potential than at stronger gravitational potential. This will result in an increase in the gravitational mass of electrons and atoms when they are accelerated toward stronger gravitational potential due to the de Broglie relation [20]. This leads to the mathematical formulation of gravitational mass dilation as follows:

$$m_\mathrm{s} = 1/\sqrt{1 - 2GM/rc^2}\, m_\mathrm{h}. \tag{2}$$

To explain the effect of gravity on chemical reactions, a gedanken experiment is carried out in which a chemical system is drifted towards the source of gravity of some heavy planet with mass M. Or, in other words, one chemical reaction is carried out at a height "h" from the surface of a heavy planet, *i.e.*, at a weaker gravitational field, and another chemical reaction is carried out at the surface of a heavy planet with mass M, provided temperature and pressure are the same at two positions in the gravitational field. All physical quantities of this chemical system that undergo a change in magnitude with a change in the strength of the gravitational field will be defined by a subscript "s" at a stronger gravitational field, *i.e.*, near the surface of a heavy planet, and denoted by a subscript "h" at a weaker gravitational field, *i.e.*, away from the surface of a heavy planet. In this work, all mathematical relations with subscripts "s" and "h" refer to the position of the chemical system at the surface of a heavy planet and at height "h" from the surface of a heavy planet, respectively. Gravitational transformations express how any particular physical quantity "Y" of the chemical system under study changes in magnitude when moving the chemical system from a weaker gravitational potential "Y_h" to a stronger gravitational potential "Y_s". In gravitational transformations, "Y_s" and "Y_h" are related to one another by a factor "$\xi = 1/\sqrt{1 - 2GM/rc^2}$," where M is the mass of the heavy planet and r is the radial coordinate of the observer [3]. Chemical reactions in this thought experiment are conducted in the gravitational field of a planet with a mass M. When some physical quantity "Y" of the chemical system under study increases in magnitude on moving towards a gravity source, *i.e.*, at a stronger gravitational field than gravitational transformation, the physical quantity "Y" of the chemical system will be mathematically expressed as "$Y_\mathrm{s} = \xi Y_\mathrm{h}$". Like in the gravitational transformation of mass given by Eq. (2), the mass of a particle "m_s" at a stronger gravitational field is greater than the mass of a particle "m_h" at a weaker gravitational field because "m_h" is multiplied by a mathematical factor "$\xi = 1/\sqrt{1 - 2GM/rc^2}$" that will always be greater than unity. Similarly, in other types of gravitational transformation, when some physical quantity "Y" of the chemical system under study decreases in magnitude on moving toward the gravity source, *i.e.*, at a stronger gravitational field, the physical quantity "Y" of the chemical system will be mathematically expressed as $Y_s = \xi^{-1}Y_h$. Therefore, in this type of gravitational transformation, "Y_s" will be smaller in magnitude than "Y_h" because it is divided by a mathematical factor "$\xi = 1/\sqrt{1 - 2GM/rc^2}$" that will always be greater than unity. For convenience, let us call "$Y_s = \xi Y_h$" the α-gravitational transformation and "$Y_s = \xi^{-1}Y_h$" the β-gravitational transformation. Thus, the gravitational transformation of mass is an α-gravitational transformation. The exact value of any particular physical quantity "Y" of the chemical system will be one in space in the absence of any gravitational field.

3 Gravitational transformations in statistical mechanics

Heisenberg's time energy uncertainty principle dictates that the greater the spacing between two quantum levels of a system, the longer the system can survive in that excited quantum level. Electronic transitions are the quickest quantum jumps in molecules, followed by vibrational transitions and, at the end, rotational transitions. This hierarchy of quantum jumps in molecules is a direct consequence of the uncertainty principle [21–23]. If a molecule in an excited jth quantum state is moved near the source of gravity, *i.e.,* at stronger gravitational potential from some weaker gravitational potential with appreciable height "h," then the lifetime of this excited state in jth quantum level will be stretched due to slower passage of time near the surface of the planet, *i.e.*, stronger gravitational field and will be mathematically expressed as

$$\langle \Delta t \rangle_s = \xi \langle \Delta t \rangle_h. \tag{3}$$

For this jth quantum state, the Heisenberg time energy uncertainty relation can be formulated as [24]

$$\langle \Delta \varepsilon_j \rangle_s \langle \Delta t \rangle_s \geq \hbar. \tag{4}$$

Due to slowing down of time near the source of gravity lifetime of an excited particle in some jth quantum state has α-gravitational transformation, *i.e.* "$\langle \Delta t \rangle_s = \xi \langle \Delta t \rangle_h$" [3]. In order to keep the Heisenberg time energy uncertainty valid in the entire gravitational field of the planet with mass M, the energy spacing between the quantum will have a β-gravitational transformation, *i.e.,*

$$\langle \Delta \varepsilon_j \rangle_s = \xi^{-1} \langle \Delta \varepsilon_j \rangle_h. \tag{5}$$

Thus, from Eq. (5), it can be inferred that near the source of gravity, *i.e.* at stronger gravitational field energy, the spacing between the quantum states will decrease, resulting in slower decay of higher excited quantum states to lower quantum states. From spectroscopic signatures of molecules following inequalities, there exists in nature electronic, vibrational, and rotational transitions of molecules at room temperature, which can be written for stronger gravitational potential as [24]

$$(\Delta \varepsilon_{\text{elec}})_s \ggg (k_B)_s T, \tag{6}$$

$$(\Delta \varepsilon_{\text{vib}})_s > (k_B)_s T, \tag{7}$$

$$(\Delta \varepsilon_{\text{rot}})_s \cong (k_B)_s T. \tag{8}$$

Inequalities of Eqs (6)–(8) for electronic, vibrational, and rotational transitions of molecules at room temperature should symmetrically also exist at the weaker gravitational field, *i.e.,*

$$(\Delta \varepsilon_{\text{elec}})_h \ggg (k_B)_h T, \tag{9}$$

$$(\Delta \varepsilon_{\text{vib}})_h > (k_B)_h T, \tag{10}$$

$$(\Delta \varepsilon_{\text{rot}})_h \cong (k_B)_h T. \tag{11}$$

The β-gravitational transformation of energy spacing will result in the β-gravitational transformation of the Boltzmann constant, *i.e.*, $\langle k_B \rangle_s = \xi^{-1} \langle k_B \rangle_h$. Thus, moving the system toward the source of gravity, *i.e.*, stronger gravitational potential, also results in a decrease in the magnitude of the Boltzmann constant along with the squeezing of energy spacing of quantum states.

3.1 Maxwell Boltzmann distribution law

The Maxwell Boltzmann distribution law, which mathematically defines the population of particles in the jth quantum state with energy ε_j at stronger gravitational potential can be defined as [25]

$$\langle n_j \rangle_s = \exp\left(-\frac{(\varepsilon_j)_s}{(k_B)_s T} \right). \tag{12}$$

Equating β-gravitational transformations of energy spacing between different quantum levels of molecules and Boltzmann constant in Eq. (12) mathematically shows that the gravitational field will not affect the population of molecules or particles in any jth quantum level, *i.e.*,

$$\langle n_j \rangle_{\mathrm{s}} = \langle n_j \rangle_{\mathrm{h}} = n_j. \tag{13}$$

3.2 Molecular partition function

Maxwell Boltzmann's statistics is the most successful theoretical explanation of the distribution of atoms and molecules among various energy states accessible to them in thermal equilibrium. Weaker temperature and low density switch off the quantum effects [25,26]. The product of translational, rotational, vibrational, and electronic partition functions gives the total partition function for Maxwell Boltzmann statistics. When a chemical system drifts toward a stronger gravitational potential, then the total partition function can be mathematically expressed in terms of individual translational, rotational, vibrational, and electronic partition functions as

$$(Q_{\mathrm{total}})_l = \frac{1}{N!}(q^{\mathrm{T}})_{\mathrm{s}}^{\mathrm{N}}(q^{\mathrm{R}})_{\mathrm{s}}^{\mathrm{N}}(q^{\mathrm{V}})_{\mathrm{s}}^{\mathrm{N}}(q^{\mathrm{E}})_{\mathrm{s}}^{\mathrm{N}}. \tag{14}$$

3.2.1 Translational partition function

When the system of molecules of mass m interacting in volume V drifted toward a stronger gravitational field, the translational partition function for them can be defined as [25,26]

$$(q^{\mathrm{T}})_{\mathrm{s}} = \left(\frac{2\pi m_{\mathrm{s}}(k_{\mathrm{B}})_{\mathrm{s}}T}{h^2}\right)^{\frac{3}{2}} V. \tag{15}$$

Equating the α-gravitational transformations of mass and β-gravitational transformations of the Boltzmann constant in Eq. (15) mathematically shows that the gravitational field will not affect the translation molecular partition of molecules, *i.e.*,

$$(q^{\mathrm{T}})_{\mathrm{s}} = (q^{\mathrm{T}})_{\mathrm{h}} = q^{\mathrm{T}}. \tag{16}$$

3.2.2 Rotational temperature and the rotational partition function

When the system of rotating diatomic molecules drifts toward the source of gravity, then at stronger gravitational potential, their rotational temperature can be formulated as [25,26]

$$(\Theta_{\mathrm{R}})_{\mathrm{s}} = \frac{hcB_{\mathrm{s}}}{(k_{\mathrm{B}})_{\mathrm{s}}}. \tag{17}$$

While the rotational constant at stronger gravitational potential can be formulated as

$$B_{\mathrm{s}} = \frac{h}{8\pi^2 cI_{\mathrm{s}}}. \tag{18}$$

As the α-gravitational transformation of the electron mass at a stronger gravitational field will increase, according to Heisenberg's uncertainty principle, *i.e.*, "$m\Delta v\Delta x \geq \hbar/2$," the velocity of electron revolving should decrease with the same factor "ξ^{-1}" rendering the total momentum of electron unchanged that keeps the bond length the same at all gravitational potentials. The α-gravitational transformations of the mass will also make the moment of inertia have α-gravitational transformation, *i.e.*, $I_{\mathrm{s}} = \xi I_{\mathrm{h}}$ [25,26]. The α-gravitational transformation of the moment of inertia will make the rotational constant "B_{s}" to undergo β-gravitational transformation, *i.e.*,

$$B_{\mathrm{s}} = \xi^{-1}B_{\mathrm{h}}. \tag{19}$$

Equating the β-gravitational transformations of the rotational constant and of the Boltzmann constant in Eq. (17) mathematically, that the gravitational field will not affect the rotational temperature of molecules, *i.e.*,

$$(\Theta_{\mathrm{R}})_{\mathrm{s}} = (\Theta_{\mathrm{R}})_{\mathrm{h}} = \Theta_{\mathrm{R}}. \tag{20}$$

The rotational partition function in terms of rotational temperature at stronger gravitational potential can be defined as

$$(q^{\mathrm{R}})_{\mathrm{s}} = \left(\frac{T}{\sigma(\Theta_{\mathrm{R}})_{\mathrm{s}}}\right). \tag{21}$$

From Eq. (21), it follows that the rotation will remain the same in all gravitational potential irrespective of its position in it, *i.e.*,

$$(q^{\mathrm{R}})_{\mathrm{s}} = (q^{\mathrm{R}})_{\mathrm{h}} = q^{\mathrm{R}}. \tag{22}$$

3.2.3 Vibrational temperature and the vibrational, rotational partition function

When the system containing vibrating molecules drifts toward the source of gravity, *i.e.*, near the surface of the planet, then the vibrational partition function at a stronger gravitational potential is mathematically formulated as [25,26]

$$(q^{\mathrm{V}})_{\mathrm{s}} = \frac{1}{1 - \frac{(\Theta_{\mathrm{vib}})_{\mathrm{s}}}{T}}. \tag{23}$$

The vibrational temperature for this system of vibrating molecules at a stronger gravitational potential is formulated as

$$(\Theta_{\text{vib}})_{\text{s}} = \frac{h\upsilon_{\text{s}}}{(k_{\text{B}})_{\text{s}}}. \tag{24}$$

As the α-gravitational transformation of time frequency is inversely related to time and will have a β-gravitational transformation $\upsilon_{\text{s}} = \xi^{-1}\upsilon_{\text{h}}$, the frequency of molecules behaving as harmonic oscillators at a stronger gravitational potential will decrease because the mass of atoms will increase at a stronger gravitational potential, and they will oscillate much slower at a stronger gravitational potential than at a weaker gravitational potential.

Thus, β-gravitational transformations of the Boltzmann constant and gravitational frequency will keep the vibrational temperature constant throughout the gravitational field, *i.e.*,

$$(\Theta_{\text{vib}})_{\text{s}} = (\Theta_{\text{vib}})_{\text{h}} = \Theta_{\text{vib}}. \tag{25}$$

It follows from Eq. (25) that the vibrational temperature remains unchanged at different gravitational potentials, so this renders the vibrational partition function to remain unchanged with a change in the strength of the gravitational field, *i.e.*,

$$(q^{\text{V}})_{\text{s}} = (q^{\text{V}})_{\text{h}} = q^{\text{V}}. \tag{26}$$

3.2.4 Electronic temperature and the electronic partition function

When a system of atoms and molecules with well-defined electronic levels drifts toward the source of gravity, then at a stronger gravitational field, the electronic partition function for these atoms and molecules can be formulated in terms of electronic temperature as [25,26]

$$(q^{\text{E}})_{\text{s}} = \sum_{i}^{N} g_i \exp\left(-\frac{(\Theta_{\text{E}})_{\text{s}}}{T}\right). \tag{27}$$

The electronic temperature for these atoms and molecules at stronger gravitational potential will be

$$(\Theta_{\text{E}})_{\text{s}} = \frac{h(\varepsilon_i^{\text{E}})_{\text{s}}}{(k_{\text{B}})_{\text{s}}}. \tag{28}$$

Again, the β-gravitational transformations of the Boltzmann constant and energy levels straightforwardly give

$$(\Theta_{\text{E}})_{\text{s}} = (\Theta_{\text{E}})_{\text{h}} = \Theta_{\text{E}}. \tag{29}$$

From Eq. (29), it is clear that the electronic temperature will not be affected by the force of gravity, which will render the electronic partition function to have the same magnitude in the entire gravitational field:

$$(q^{\text{E}})_{\text{s}} = (q^{\text{E}})_{\text{h}} = q^{\text{E}}. \tag{30}$$

From all respective individual partition functions, it can be inferred that the total molecular partition function will remain the same in the entire gravitational field, *i.e.*,

$$(Q_{\text{total}})_{\text{s}} = (Q_{\text{total}})_{\text{h}} = Q_{\text{total}} = Q. \tag{31}$$

Thus, gravity does not affect the magnitude of the molecular partition function of the chemical system.

4 Gravitational transformations in statistical thermodynamics

Statistical mechanics gives the molecular-level view of all the macroscopic thermodynamic quantities, such as internal energy, free energy, and entropy. In statistical thermodynamics, all properties of the system in thermodynamics equilibrium are encoded in terms of the partition function Q. All thermodynamic state variables and equilibrium constants are mathematically expressed in terms of the partition function [25,26]. For a chemical system drifted toward the source of gravity, all thermodynamic state functions, *i.e.*, integral energy U, enthalpy H, entropy S, Gibbs Helmholtz energy A, and Gibbs free energy G at stronger gravitational potential are mathematically expressed as

$$U_{\text{s}} = -N(k_{\text{B}})_{\text{s}}\left(\frac{\partial Q}{\partial T}\right)_{\text{V}}, \tag{32}$$

$$H_{\text{s}} = T\left[(k_{\text{B}})_{\text{s}}T\left(\frac{\partial}{\partial T}\ln Q\right)_{\text{V}} + V(k_{\text{B}})_{\text{s}}\left(\frac{\partial}{\partial V}\ln Q\right)_{\text{T}}\right], \tag{33}$$

$$S_{\text{s}} = (k_{\text{B}})_{\text{s}}T\left(\frac{\partial \ln Q}{\partial T}\right) + (k_{\text{B}})_{\text{s}}\ln Q, \tag{34}$$

$$A_{\text{s}} = (k_{\text{B}})_{\text{s}}T\ln Q, \tag{35}$$

$$G_{\text{s}} = (k_{\text{B}})_{\text{s}}T\left[(\ln Q) - V\left(\frac{\partial}{\partial V}\ln Q\right)_{\text{T}}\right]. \tag{36}$$

The β-gravitational transformation of the Boltzmann constant will straightforwardly make all thermodynamic state functions exhibit β-gravitational transformations, *i.e.*,

$$U_{\text{s}} = \xi^{-1}U_{\text{h}}, \tag{37}$$

$$H_{\text{s}} = \xi^{-1}H_{\text{h}}, \tag{38}$$

$$S_{\text{s}} = \xi^{-1}S_{\text{h}}, \tag{39}$$

$$A_{\text{s}} = \xi^{-1}A_{\text{h}}, \tag{40}$$

$$G_s = \xi^{-1} G_h. \tag{41}$$

Thus, all thermodynamic state functions of the chemical system under study will decrease in magnitude when the chemical system drifts toward the source of gravity, *i.e.,* at the stronger gravitational field. The β-gravitational transformations of these thermodynamic state functions are used to explain the quasi-equilibrium existing between the reactants and activated complexes during chemical reactions.

5 Gravitational transformations in chemical kinetics

To theoretically explain the effect of the strength of the gravitational field on chemical reactions, the necessary mathematical forms of the rate laws in four basic theories of chemical kinetics, meeting the requirements of general relativity, are derived in the following.

5.1 Gravitational transformation of the rate constant from transition state theory

Transition state theory, which separates the reactants and products on the potential energy surface while taking into account the Born–Oppenheimer approximation, formulates an expression for the thermal rate constant. The Maxwell Boltzmann distribution is used to distribute reactants, products, and transition states among their different quantum states even in the absence of an equilibrium between the reactant and product molecules [27–29]. A special type of equilibrium exists between the reactants and activated complexes, called quasi-equilibrium. In the transition state, the motion along the reaction coordinate is separated from the other motions and explicitly treated as a translational motion in a classical regime. Rice–Ramsperger–Kassel–Marcus (RRKM) theory also exclusively treats the motion of the transition state along the reaction coordinate as a simple translational motion [30]. If a chemical system drifts toward the source of gravity, then according to time energy, Heisenberg uncertainty principles at a stronger gravitational field lifetime of the transition state $(\Delta t)_s$ must be greater than $\hbar/(k_B)_s T$ to execute translation along the reaction coordinate. Mathematically, it can be written as $(k_B)_s T(\Delta t)_s \geq \hbar$, which according to gravitational time dilation naturally leads to β-gravitational transformation of the Boltzmann constant, *i.e.,* $(k_B)_s = \xi^{-1}(k_B)_h$. The Eyring equation for an nth-order reaction in thermodynamic terms, at stronger gravitational field, is defined as [31,32]

$$(k_n)_s = \kappa \frac{(k_B)_s T}{h[(c^o)]^{(n-1)}} \exp\left(\frac{(\Delta S^\dagger)_s}{R_s}\right) \exp\left(\frac{(-\Delta H^\dagger)_s}{R_s T}\right). \tag{42}$$

Placing β-gravitational transformations of the Boltzmann constant, enthalpy, and entropy gives

$$(k_n)_s = \xi^{-1}(k_n)_h. \tag{43}$$

The Arrhenius factor gives the quantitative expression for the number of reactant molecules crossing the energy barrier and transforming into products. At stronger gravitational potential, it transforms as [24–27]

$$A_s = \exp[-(\Delta n - 1)] \frac{(k_B)_s T}{[h(c^o)]^{(n-1)}} \exp\left(\frac{(\Delta S^\dagger)_s}{R_s}\right). \tag{44}$$

Placing β-gravitational transformations, the Boltzmann constant, the universal gas constant, and entropy gives

$$A_s = \xi^{-1} A_h. \tag{45}$$

5.2 Gravitational transformation of the rate constant from collision theory of bimolecular reactions

Consider a chemical system under study in which the bimolecular chemical reaction is conducted, *i.e.,* A + B → P. The best candidate for explaining the kinetics of such reactions is collision theory. The collision theory for reaction rates treats the molecules of reactants as hard spheres colliding with each other, expressing the rate of the chemical reaction with the number of collisions. The theory mathematically expresses the rate of reaction in terms of three important parameters: (i) collision frequency, (ii) collision cross-section, and (iii) relative velocity. When this chemical system of the biomolecular reaction is drifted toward the source of gravity, *i.e.,* at a stronger gravitational field, then the rate constant in terms of the collision cross section and relative velocity of colliding molecules at a stronger gravitational field is stated as [31,32]

$$(k_2)_s = N_A \sigma_{AB} (\nu_r)_s. \tag{46}$$

At a stronger gravitational field, the relative velocity between the colliding atoms and molecules is mathematically expressed as

$$\langle \nu_r \rangle_s = \left(\frac{8(k_B)_s T}{\pi \mu_s}\right)^{\frac{1}{2}}. \tag{47}$$

Substituting the β-gravitational transformation of the Boltzmann constant and α-gravitational transformation of mass in Eq. (47) gives the β-gravitational transformation of the relative velocity as

$$\langle v_\mathrm{r}\rangle_\mathrm{s} = \xi^{-1}\langle v_\mathrm{r}\rangle_\mathrm{h}. \tag{48}$$

The relative velocity between the colliding atoms and molecules will be slowed at a stronger gravitational potential due to the β-gravitational transformation of the Boltzmann constant and mass. This is totally compatible with slower time flow at a stronger gravitational field, as described by general relativity. At a stronger gravitational field, events slow down, and thus, collisions among molecules also slow down near the source of gravity. Substituting the β-gravitational transformation of the relative velocity from Eq. (48) into Eq. (46) again gives the β-gravitational transformation of the rate constant,

$$\langle k_2\rangle_\mathrm{s} = \xi^{-1}\langle k_2\rangle_\mathrm{h}. \tag{49}$$

The collision frequency for bimolecular reaction is mathematically defined in terms of mole densities $\rho_\mathrm{A}\rho_\mathrm{B}$, collision cross-section, and relative velocity [31,32]. At a stronger gravitational field, the collision frequency can be expressed as

$$(Z_\mathrm{AB})_\mathrm{s} = N_\mathrm{A}\sigma_\mathrm{AB}(v_\mathrm{r})_\mathrm{s}\rho_\mathrm{A}\rho_\mathrm{B}. \tag{50}$$

Substituting β-gravitational transformation of the relative velocity into Eq. (50) reveals that the collision frequency also reduces at a stronger gravitational potential,

$$(Z_\mathrm{AB})_\mathrm{s} = \xi^{-1}(Z_\mathrm{AB})_\mathrm{h}. \tag{51}$$

The β-gravitational transformation of the collision frequency again explains that at a stronger gravitational field, molecules will collide at a slower rate. Thus, gravity slows down the molecular collisions.

5.3 Gravitational transformation of the rate constant from Marcus' theory of electron transfer

Marcus's theory is the most successful theoretical model for electron transfer reactions in general and, most importantly, for the outer sphere electron transfer reactions [33–37]. This model is based on the rearrangement of solvent molecules around the reactant ions to configure it for a favorable electron transfer. There is a solvent arrangement around each reactant ion, having Gibb's free energy G as a minimum, and a change in this solvent structure shoots up its free energy. For successful electron transfer, the transition state is attained by a reduction in the separation between the two reactant ions and a reorganization of the solvent structure around each of them. A reaction coordinate for electron transfer can be regarded as a combination of these ion–ion separations and solvent reorganization coordinates. Gibb's free energy of reactants and products *versus* reaction coordinates behave as a parabolic function. The point of intersection of two parabolic curves corresponding to free energies of reactants and products locates the transition state. Marcus's theory mathematically encodes the activation energy based in terms of reorganization energy. Consider a chemical system in which the $\mathrm{A}^{\mathrm{ZA}} + \mathrm{B}^{\mathrm{ZB}} \rightarrow \mathrm{A}^{\mathrm{ZA}\,+\,\Delta\mathrm{Z}} + \mathrm{B}^{\mathrm{ZB}\,-\,\Delta\mathrm{Z}}$ electron transfer reaction drifted toward the source of gravity. Then, at a stronger gravitational field, the Marcus expression for the rate constant of this electron transfer reaction can be expressed as [33–37],

$$(k_\mathrm{AB})_\mathrm{s} = (Z_\mathrm{AB})_\mathrm{s}\exp\left(\frac{-((\Delta G^\mathrm{o}_\mathrm{AB})_\mathrm{s} + \lambda_\mathrm{s})^2}{4\lambda_\mathrm{s}R_\mathrm{s}T}\right). \tag{52}$$

Here, λ_s is the reorganization energy and quantitatively explains the energy required to reorganize the system structure from initial to final coordinates, avoiding hopping between any two different electronic states. Like other thermodynamic state functions, reorganization energy should have the same β-gravitational transformation. The reorganization energy is composed of solvation and vibrational $(\lambda_\mathrm{o})_\mathrm{s}$ and $(\lambda_i)_\mathrm{s}$ components. At a stronger gravitational field, the vibrational reorganization energy $(\lambda_i)_\mathrm{s}$ can be formulated in terms of a reduced force constant $(k_j)_\mathrm{s}$ of the jth normal mode coordinates of reactants q_j^r and products q_j^p as

$$(\lambda_i)_\mathrm{s} = \frac{1}{2}\sum_j (k_j)_\mathrm{s}(q_j^\mathrm{r} - q_j^\mathrm{p})^2. \tag{53}$$

At stronger gravitational fields, the reduced force constant $(k_j)_\mathrm{s}$ of the jth normal mode can be defined as $(k_j)_\mathrm{s} = 4\pi^2\omega_\mathrm{s}^2\mu_\mathrm{s}$. The β-gravitational transformation of the reduced mass "$\mu_\mathrm{s} = \xi\mu_\mathrm{h}$" and oscillation frequency "$\omega_\mathrm{s} = \xi^{-1}\omega_\mathrm{h}$" will straightforwardly give the β-gravitational transformation of the force constant of the jth normal mode $(k_j)_\mathrm{s} = \xi^{-1}(k_j)_\mathrm{h}$. Using this β-gravitational transformation for the force constant in Eq. (53) evaluates the β-gravitational transformation of vibrational reorganization energy,

$$(\lambda_i)_\mathrm{s} = \xi^{-1}(\lambda_i)_\mathrm{h}. \tag{54}$$

The solvation reorganization energy for Δe charge transferred between the reactants can be mathematically defined in terms of reactants ionic radii a_1 and a_2, their center-to-center separation distance W, the refractive index "n_{solv}", and the dielectric constant "$\varepsilon_{\mathrm{solv}}$" of the solvent, which at a stronger gravitational field can be defined as

$$(\lambda_o)_s = (\Delta e)^2\left(\frac{1}{2a_1} + \frac{1}{2a_2} - \frac{1}{W}\right)\left(\frac{1}{(n_{\mathrm{solv}})_s^2} - \frac{1}{(\varepsilon_{\mathrm{solv}})_s}\right). \quad (55)$$

The β-gravitational transformation of the mass will then certainly give the β-gravitational transformation for the dielectric constant, *i.e.*, $(\varepsilon_{\mathrm{solv}})_s = \xi(\varepsilon_{\mathrm{solv}})_h$ and β-gravitational transformation for the refractive index of solvent, *i.e.*, $(n_{\mathrm{solv}})_s = \xi^{-1/2}(n_{\mathrm{solv}})_h$. Substituting the gravitational transformation of the refractive index and dielectric constant in Eq. (55) gives

$$(\lambda_o)_s = \xi^{-1}(\lambda_o)_h. \quad (56)$$

Therefore, from Eqs (54) and (56), the gravitational transformation for total reorganization energy can be formulated as $\lambda_s = \xi^{-1}\lambda_h$. Thus, β-gravitational transformations for free energy, reorganization energy, collision frequency, and ideal gas constant in Eq. (52) yields

$$(k_{AB})_s = \xi^{-1}(k_{AB})_h. \quad (57)$$

Now, consider an electron transfer reaction from a different perspective. Let A, B be reactants, and X^*, X be hypothetical initial and final thermodynamic states of the system defined as intermediates. Then,

$$A + B \rightleftharpoons X^* \rightleftharpoons X \rightarrow P. \quad (58)$$

When the reactants approach each other to undergo an electron-transfer reaction, suitable solvent fluctuation leads to the formation of the state X^*, which has the same atomic configuration of the reacting pair and of the solvent as that of the activated complex, while it has the electronic configuration of the reactant. X^* has two choices: either to form the reactant following the disorganization of some of the oriented solvent molecules or transform to state X by undergoing an electronic transition. X possesses the same atomic configuration as that of X^* but it has the electronic configuration of the products. The pair of states X^* and X together constitutes the activated complex. Now, consider that the chemical system carrying out such an electron transfer reaction is drifting toward the source of gravity. At a stronger gravitational field, the rate constant for the electron transfer reaction is expressed in terms of electronic coupling $(H_{AB})_s$ between the reaction intermediates of the electron transfer reaction (*i.e.*, the overlap of the electronic wave functions of the two states) is formulated as [37]

$$(k_{et})_s = \frac{2\pi}{\hbar}(H_{AB})_s^2\frac{1}{\sqrt{4\pi\lambda_s R_s T}}\exp\left(\frac{-((\Delta G^o)_s + \lambda_s)^2}{4\lambda_s R_s T}\right). \quad (59)$$

The β-gravitational transformations for free energy, *i.e.*, $(G^o)_s = \xi^{-1}(G^o)_h$, electronic coupling $(H_{AB})_s = \xi^{-1}(H_{AB})_h$, universal gas constant $R_s = \xi^{-1}R_h$, and total reorganization energy $\lambda_s = \xi^{-1}\lambda_h$ results in the following gravitational transformation for the electron transfer rate constant:

$$(k_{et})_s = \xi^{-1}(k_{et})_h. \quad (60)$$

5.4 Gravitational transformation of the RRKM rate constant

If a system carrying out an unimolecular reaction drifted toward the source of gravity, then according to RRKM theory, which unifies statistical RRK theory with transition state theory at high-pressure limit, it gives the following expression for the rate constant at a stronger gravitational field [30]:

$$(k_{\mathrm{uni}}^{\infty})_s = \frac{(k_B)_s T}{h}\frac{Q_r^{\dagger}Q_v^{\dagger}\exp(-(E_0)_s/(k_B)_s T)}{Q_r Q_v}. \quad (61)$$

The β-gravitational transformations of the Boltzmann constant and activation energy also give the following β-gravitational transformation for the unimolecular rate constant,

$$(k_{\mathrm{uni}}^{\infty})_s = \xi^{-1}(k_{\mathrm{uni}}^{\infty})_h. \quad (62)$$

5.5 Gravitational transformation of the rate of reaction

From the basic knowledge of chemical kinetics, it is well known that the rate of a chemical reaction is defined as the rate of change of concentration "C" with respect to time t [31,32]. In the case of a gas-phase reaction, "C" is replaced with pressure "P" and the number of molecules or atoms "N" in the solid phase reactions (nuclear reactions). Now, consider a chemical system with a concentration "C" toward the source of gravity. Then, at a low gravitational field rate, the equation is formulated as

$$(r_n)_s = \frac{d[C]}{dt_s} = (k_n)_s[C]^n. \quad (63)$$

Substituting the β-gravitational transformation of the rate constant in Eq. (63) gives the β-gravitational transformation of the rate of the chemical reaction, *i.e.*,

$$(r_n)_s = \xi^{-1}(r_n)_h. \quad (64)$$

Thus, from Eq. (64), the rate of the reaction at a stronger gravitational field, *i.e.*, near the surface of the planet, is slower than that at a weaker gravitational field, *i.e.*, at an appreciable height from the surface of the planet.

5.6 Gravitational transformation of half-life

If a chemical system has an initial concentration of reactants, C_o drifts toward the center of gravity. Then, the half-life period during which one-half of the initial concentration C_o of a reactant converts into products at a stronger gravitational field is defined as

$$(t_{1/2})_s = \frac{J}{(k_n)_s [C_o]^{(n-1)}}. \tag{65}$$

Here, J is the coefficient for the nth-order reaction. Substituting the β-gravitational transformation of the rate constant, *i.e.*, $(k_n)_s = \xi^{-1}(k_n)_h$ in Eq. (65) simply gives the gravitational half-life equation

$$(t_{1/2})_s = \xi (t_{1/2})_h. \tag{66}$$

Gravitational transformation for half-life is completely the mirror image of Einstein's gravitational time dilation equation. This can explain time dilation at the molecular level, as Einstein's equation does in the physical world.

5.7 Relativistic equilibrium constant

Consider a chemical reaction at chemical equilibrium [25],

$$\text{aA} + \text{bB} \rightleftharpoons \text{cC} + \text{dD}. \tag{67}$$

Let the system where this chemical reaction at chemical equilibrium is carried out drift toward the surface of the heavy planet, and then the equilibrium constant for this reaction is expressed in terms of partition function at a stronger gravitational field as

$$(K_{eq})_s = \frac{[Q_C]^c [Q_D]^d}{[Q_A]^a [Q_B]^b} \exp\left(\frac{-\langle \Delta\varepsilon_o \rangle_s}{R_s T}\right). \tag{68}$$

Since the difference in zero-point energies of the reactants and products "$\langle \Delta\varepsilon_o \rangle_l$" and ideal gas constant undergoes β-gravitational transformations; thus, both together inhibit any change in the magnitude of the chemical equilibrium constant in the entire gravitational field, *i.e.*,

$$(K_{eq})_s = (K_{eq})_h = K_{eq}. \tag{69}$$

The system at chemical equilibrium should appear the same irrespective of its position in the gravitational field. Since chemical equilibrium constant is also defined as the ratio of rate constants of forward and backward reactions of the chemical system at equilibrium, *i.e.* [25],

$$K_{eq} = (k_f)_s / (k_b)_s. \tag{70}$$

Substituting the β-gravitational transformations of the forward and backward rate constants of chemical reactions making up chemical equilibrium in Eq. (70) will also keep the chemical equilibrium constant in the whole gravitational field. Thus, the amount of reactants and products in chemical equilibrium with one another remains the same, independent of the position of the chemical system in the gravitational field.

6 Results and discussion

6.1 Discussion on gravitational statistical thermodynamics

The present theory shows that the Boltzmann constant is consistent with the gravitational transformation of energy spacing between permitted quantum levels of molecules since the molecular transition between two states is dictated by the spacing among them, which results in electronic transitions being quicker than vibronic transitions and vibronic transitions to be quicker than rotational transitions. A general theory of relativity works on the principle that time flows slower near the surface of the heavy planet, *i.e.*, a stronger gravitational field results in slower de-excitation of an excited state. This can only be afforded at the expense of a decrease in energy spacing between different quantum states, *i.e.*, the β-gravitational transformation of energy spacing between quantum levels, *i.e.* $(\Delta\varepsilon)_s = \xi^{-1}(\Delta\varepsilon)_h$. Experimentally, it is known that molecules possessing lighter isotopes of elements constituting them have elevated quantum levels than those with heavier isotopes [38]. Thus, based on this observation, the gravitational mass dilation fully supports the gravitational transformation of energy spacing between different quantum levels of the system under study. In all three types of statistics, *i.e.*, Fermi–Dirac statistics, Bose–Einstein statistics, and Maxwell Boltzmann statistics describing the distribution of the total number of particles among different quantum states in different scenarios, there exists a common exponential factor, *i.e.*, $w_s = \exp(-(\Delta\varepsilon)_s/(k_B)_s T)$ [25,26]. The β-gravitational transformations of energy levels and Boltzmann constant together keep this exponential factor constant in the entire gravitational field.

Therefore, the partition function of all three types of statistics and their distribution in the respected permitted energy states do not change with the change in the strength of the gravitational field due to this exponential factor. This will result in the number of molecules in particular energy levels remaining the same irrespective of the position of the system in the entire gravitational field. Thus, the ratio of the distribution of the total energy among the total number of molecules comprising the system under study and all of their internal degrees of freedom (translational, vibrational, rotational, and electronic) will remain the same irrespective of the position of the system in the gravitational field. At stronger gravitational potential, the mass of the molecules increases, which will result in the α-gravitational transformation, *i.e.*, $I_{\mathrm{s}} = \xi I_{\mathrm{h}}$. To conserve the law of conservation of angular momentum, the angular velocity decreases at stronger gravitational potential, *i.e.*, $\omega_{\mathrm{s}} = \xi^{-1}\omega_{\mathrm{h}}$. This will result in a decrease of rotational speed of molecules at a stronger gravitational field, which supports the fact that time flows slowly near the source of gravity. The α-gravitational transformation of rotational inertia of molecules dictates the rotational constant to have β-gravitational transformation at a stronger gravitational potential, *i.e.*, $B_{\mathrm{s}} = \xi^{-1}B_{\mathrm{h}}$. This again supports the gravitational time dilation. The β-gravitational transformations of the rotational constant and Boltzmann constant keep the rotational temperature the same at all positions in the gravitational field. This makes the rotational partition function remain the same at all positions in the entire gravitational field. Since molecules execute vibrations, the α-gravitational transformation of the mass of atoms at a stronger gravitational field will decrease the vibrational frequencies of all vibrational modes present in the molecules, resulting in the β-gravitational transformation of vibrational frequency, *i.e.*, $\upsilon_{\mathrm{s}} = \xi^{-1}\upsilon_{\mathrm{h}}$, which again supports the slow passage of time near the source of gravity. As at the surface of heavy planet, time flows slowly compared to weaker gravitational potential, the atoms in molecules will undergo slower compressions and extensions at a stronger gravitational field. The β-gravitational transformations of the vibrational frequency and Boltzmann constant at a stronger gravitational field keep the vibrational temperature constant at all positions in the entire gravitational field. Similarly, this makes the vibrational partition function remain the same at all positions in the whole gravitational field. The electronic temperature and the electronic partition function will not change with a change in the strength of the gravitational field due to the α-gravitational transformation of mass and β-gravitational transformations of velocities of electrons and their permitted quantum states. Thus, all types of molecular partition functions, *i.e.*, translational, rotational, vibrational, and electronic, will remain the same throughout the entire gravitational potential. Thus, α-gravitational transformation of the mass of molecules and β-gravitational transformation of spacing between the quantum levels at stronger gravitational potential keeps the translational, vibrational, rotational, and electronic partition functions constant at all gravitational potentials, *i.e.*, stronger and weaker potentials. Since the translational, rotational, vibrational, and electronic temperatures had already been mathematically proved invariant under Lorentz boosts [17]. Similarly, no gravitational transformation exists for translational, rotational, vibrational, and electronic temperatures. All thermodynamic state variables are mathematically expressed in terms of partition functions together with the Boltzmann constant. The β-gravitational transformation of the Boltzmann constant will make all thermodynamic state functions decrease near the source of gravity, *i.e.*, at stronger gravitational potential. At stronger gravitational potential, the mass of particles increases, which decreases all forms of their internal motions, and, thus, all molecular transformations defining the thermodynamic state functions decrease at stronger gravitational potential, which is in accordance with the slower flow of time near the source of gravity.

6.2 Discussion on gravitational chemical kinetics

Transition state theory is the most successful and universal theory of chemical kinetics for evaluating reaction rates [39]. This theory, for the first time, coins the concept of an activated complex called transition state, which is responsible for the conversion of reactants into products by making a translational sweep over the reaction coordinate. According to the α-gravitational transformation of mass transition state, the mass will increase, *i.e.*, $m_{\mathrm{s}}^{\dagger} = \xi m_{\mathrm{h}}^{\dagger}$ near the source of gravity, *i.e.*, at a stronger gravitational field. When a chemical system is drifted toward the source of gravity, then according to the β-gravitational transformation of the velocity transition state, the velocity will decrease at a stronger gravitational field, *i.e.*, $v_{\mathrm{s}}^{\dagger} = \xi^{-1}v_{\mathrm{h}}^{\dagger}$, so this will make the momentum of the transition state to remain the same at all positions in the gravitational field, *i.e.*, $\Delta p_{\mathrm{s}} = \Delta p_{\mathrm{h}} = \Delta p$. Since the de Broglie relation shows that the mass and de Broglie wavelength associated with a transition state are inversely related to one another, *i.e.*, $\lambda_{\mathrm{s}} = h/\Delta p_{\mathrm{s}}$ [31]. As the momentum of the transition state remains same at all positions in the entire gravitational field, so the de Broglie associated with the transition state remains same in the entire gravitational potential, *i.e.*,

$\lambda_s = \lambda_h = \lambda$. This de Broglie wave associated with the transition state should not be confused with the de Broglie wave explained earlier while formulating gravitational mass dilation. In that thought experiment, the stream of atoms or electrons is pumped out straight in a beam against the gravitational potential, leading to gravitational redshift in their de Broglie wavelength, while, here, the transition states for two same reactions are discussed, which are carried out at different positions in a gravitational field, whose de Broglie wave remains the same in entire gravitational field. At a stronger gravitational field, the transition state produced will be more massive than the transition state produced at a weaker gravitational potential, so to have the same de Broglie wavelength transition state at different gravitational fields, it should possess smaller velocity at the stronger gravitational field, *i.e.* near the source of gravity. This fully supports the idea that time flows slower near the source of gravity. According to Heisenberg's uncertainty relation, the reaction coordinate can only be sufficient to accommodate the transition state if it is of size equal to the de Broglie wavelength, *i.e.*, $(\Delta q)_s \geq \lambda_s/2\pi$ [17]. Since the de Broglie wavelength of the transition state is the same at all positions in the gravitational field, this keeps the reaction coordinate the same at all positions in the gravitational field, *i.e.*, $(\Delta q)_s = (\Delta q)_h = \Delta q$. The accommodation of activated complexes along the reaction coordinate is mathematically defined as $\delta_s^\dagger = h/\sqrt{(2\pi m_s^\dagger (k_B)_s T)}$, and it can be shown that it remains the same at all positions in the gravitational field by β-gravitational transformation of the Boltzmann constant and α-gravitational transformation mass, *i.e.*, $\delta_s^\dagger = \delta_h^\dagger = \delta^\dagger$. At the stronger gravitational field, the average rate of the passage of activated complexes over the barrier along the coordinate can be formulated mathematically as $r_s^\dagger = \sqrt{(k_B)_s T/2\pi m_s^\dagger}$, which on substituting β-gravitational transformation of the Boltzmann constant and mass gives $r_s^\dagger = \xi^{-1} r_h^\dagger$. Therefore, at the stronger gravitational field, the transition state will have less kinetic energy and, thus, it will undergo slower translations over the reaction coordinate. The β-gravitational transformation of the Boltzmann constant equips the transition state with less kinetic energy and slows down its motion along the reaction coordinate. The rate constant of the fastest reaction possible at the stronger gravitational field will be an order of $(k_B)_s T/h$ [40]. At the stronger gravitational field, the β-gravitational transformation of the Boltzmann constant will decrease the rate constant by decreasing the frequency of the passage of reactants through the transition state. The β-gravitational transformation of rate constant holds for all types of reactions regardless of the type of kinetics they follow, *i.e.*, either zero order, first order, second order, third order, *etc.* Transitions state theory defines the Arrhenius factor in terms of thermodynamic state functions. All thermodynamic state functions and universal gas constants undergo a β-gravitational transformation, thus dictating the Arrhenius factor to have the same transformation. The Arrhenius factor, appearing as a pre-exponential factor in the rate equation, controls the frequency of the passage through the transition state. The α-gravitational transformation of a mass of reacting atoms and molecules decreases the Arrhenius at a stronger gravitational potential, which fully supports the slower passage of time near the source of gravity or the surface of the heavy planet. The rate constant gives a quantitative picture of the speed of reaction; as the rate constant decreases, the rate of reaction also decreases at the stronger gravitational potential, *i.e.,* near the source of gravity. This is shown mathematically for the first time in the current work, showing that the rate of the reaction has a gravitational transformation. Gravitational transformation of the half-life period equation, as shown in Eq. (66) again supports Einstein's gravitational time dilation. This shows a deep connection between the present theories of rates of reactions and the general theory of relativity.

Collision theory, which focuses on the kinetics of bimolecular reactions, expresses the rate of reactions as the frequency of bimolecular collisions. The rate of reaction is dictated by the number of fruitful collisions occurring per second. The frequency of collision is responsible for the rate of reaction. The rate constant in collision theory is a product of the relative velocity of colliding molecules and the collision cross-section area undergoing the bimolecular collision. The α-gravitational transformation of a mass of molecules decreases the relative velocities between the colliding molecules. The β-gravitational transformation of the Boltzmann constant also demotes the energy available per molecule, thus dropping the relative velocity between the molecules. Collision frequency defines the rate of the reaction as a product of the area of collision cross-section, mole densities, and relative velocity of the colliding molecules. Since the collision cross-section area and mole densities (concentration) remain the same at all positions in the entire gravitational field, the relative velocity decreases, which gives β-gravitational transformation of collision frequency, as shown in Eq. (51). The decrease in collision frequency of molecules at stronger gravitational field slows down the reaction rate. The β-gravitational transformation of collision frequency transformation fully agrees with the idea of slowing down time near the source of gravity given by the general theory of relativity. Since time flows slower at stronger gravitational potential, the collision frequency of the molecules also decreases near the source of gravity.

The Marcus theory is a statistical mechanical approach employing potential energy surfaces to describe several important redox processes in chemistry and biology [36,37]. These redox reactions occur on a scale much faster than the nuclear vibrations. Therefore, the nuclei do not appreciably move during the electron transfer phenomenon. During the transfer, the energies of the donor and acceptor, as well as orbitals, must match. The energy levels of the donor and acceptor orbitals in the reactants and products come in continual flux due to internal nuclear and solvent motions. For a successful transfer, the donor and acceptor molecules must attain definite geometries and suitable solvation arrangements that result in the matching of energy levels between the donor and acceptor orbitals. The nuclei of the donor and acceptor molecules relax to their optimum positions once electron transfer has occurred. The energy needed to modify the solvation sphere and internal structures, making the donor and acceptor orbital of the same energy, is defined as reorganization energy. This energy is a barrier to electron transfer and appears in two forms. One of them is vibrational reorganization energy $(\lambda_i)_\mathrm{s}$, that is the energy difference between changes in the bond length, angles, *etc.*, which occur upon electron transfer. The α-gravitational transformation of a mass of nuclei of the reacting species decreases their characteristic oscillation frequency and, thus, reduces the force constant at a stronger gravitational field, and therefore, the energy needed to bring changes in the bond length, angles, *etc.* For a successful transfer of the electron rate at the stronger gravitational field will decrease as compared to the same reaction conducted at weaker gravitational potential, as shown in Eq. (54). While the solvation reorganization energy $(\lambda_\mathrm{o})_\mathrm{s}$ that counts the energy required in the reorganization of the solvent shell is shown in Eq. (55). When the electron transfer reaction is carried out at stronger gravitational potential, the α-gravitational transformation of the mass makes the density increase. Therefore, at a stronger gravitational field, the solvent becomes denser than at a weaker gravitational potential, resulting in the α-gravitational transformations of the refractive index and dielectric constant, making the solvational reorganization energy to have β-gravitational transformation for the successful transfer of an electron, as shown in Eq. (56). The β-gravitational transformations of solvational reorganization energy and vibrational reorganization energy together make the β-gravitational transformation of total reorganization energy possible. This is similar to gravitational transformations of other thermodynamic state functions expressed earlier in this work. The electron transfer reaction occurs *via* a very slight spatial overlap of the electronic orbitals of the two reacting molecules in the activated complex. The assumption of slight overlap is defined in terms of electronic coupling between intermediates X^* and X. The intermediate state X^* has two choices: either to disappear and reform reactants or undergo electronic jump to form a state X in which the ions resemble the characteristics of products. The rate constant equation for such an electron transfer reaction has electronic coupling $(H_\mathrm{AB})_\mathrm{s}$ as a pre-exponential factor that defines the electronic overlap between the intermediates X^* and X. According to the Heisenberg uncertainty principle, *the greater the overlap, the shorter will be the lifetimes of states* X^* *and* X [35]. At a stronger gravitational field, the α-gravitational transformation of mass transformation will decrease the velocity of electrons, keeping the net momentum the same while the space occupied by these electrons remains unchanged due to the momentum-space uncertainty principle, *i.e.*, the bond length remains the same at all positions in the gravitational field. This decrease in electronic oscillations confined in the same space (orbitals) will make the spatial overlap of orbitals decrease at a stronger gravitational field, and thus, the β-gravitational transformation of electronic coupling is obtained as $(H_\mathrm{AB})_\mathrm{s} = \xi^{-1}(H_\mathrm{AB})_\mathrm{h}$. Thus, the rate constant for the electron transfer reaction decreases at stronger gravitational field and supports the slow passage of time near the source of gravity.

7 Applications

7.1 Gas-phase reaction of the hydroxyl radical with 2-methyl-1-propanol

To demonstrate the effectiveness of the present theory, we consider the example of gas-phase reactions of the hydroxyl radical with 2-methyl-1-propanol [41] conducted on the surface of the Earth. The rate constant of the reaction was experimentally measured on the surface of the Earth [41]. Now, the same reaction was carried out in a stationary laboratory named “CZ” built at a distance “h” of 939 km away from the event horizon of a Black hole named “M87” [42]. Laboratory “CZ” should be kept stationary to avoid the emergence of relativistic effects from special relativity. For observing only the effect of gravity on the rate constant of the chemical reaction under study, the temperature and pressure, *i.e.*, 298 K and 1 atm should be the same at the surface of the Earth and laboratory “CZ.” Now, the laboratory at the surface of the Earth has a weaker gravitational field as compared to the laboratory “CZ,” which has a stronger gravitational field. This is because even at a distance of 939 km, the gravity of Black hole “M87” will be much stronger than gravity at the surface of Earth [42]. As mentioned above, the physical quantities whose magnitude is affected by the strength of the gravitational field will have their exact value in free space in the absence of gravity. The Earth's surface will be at a stronger gravitational field than a laboratory in free space where there is no gravity. From Eq. (43), the mathematical relation gives a comparison of the exact rate constant of the chemical reaction "k" in free space in the absence of any gravitational field compared to the rate constant of the reaction "k_{earth}" on the surface of Earth is formulated as

$$k = k_{\mathrm{earth}}/\sqrt{1 - 2GM_{\mathrm{earth}}/R_{\mathrm{earth}}c^2}. \tag{71}$$

The laboratory "CZ" at a distance of 939 km away from the event horizon of Black hole "M87" is at a stronger gravitational field compared to the laboratory in free space where there is no gravity. From Eq. (43), the mathematical relation gives a comparison of the exact rate constant of the chemical reaction in free space in the absence of any gravitational field compared to the rate constant of the reaction "k_{M87}" conducted in laboratory "CZ" be formulated as

$$k = k_{\mathrm{M87}}/\sqrt{1 - 2GM_{\mathrm{M87}}/(R_{\mathrm{M87}} + h)c^2}. \tag{72}$$

Comparing Eqs. (71) and (72), we have the following relation:

$$\begin{aligned} k_{\mathrm{M87}} = k_{\mathrm{earth}}(&\sqrt{1 - 2GM_{\mathrm{M87}}/(R_{\mathrm{M87}} + h)c^2} \\ &/\sqrt{1 - 2GM_{\mathrm{earth}}/R_{\mathrm{earth}}c^2}). \end{aligned} \tag{73}$$

Substituting the values of the universal gravitational constant "G"; the mass of Earth "M_{earth}"; the mass of Black hole "M_{M87}"; the radius of R_{earth} and Schwarzschild radius of a black hole "R_{M87}" at a distance "h" of laboratory "CZ" from the event horizon of "M87" and the rate of chemical reaction reported on the surface of the Earth "R_{earth}" in Eq. (73) gives

$$k_{\mathrm{M87}} = k_{\mathrm{earth}}/10. \tag{74}$$

From Eq. (74), it can be inferred that in laboratory "CZ" at a distance of 939 km away from the event horizon of black hole "M87", the rate constant of the chemical reaction will be reduced ten times in magnitude than the rate constant of the same reaction on the surface of the Earth, provided the temperature and pressure are same at the surface of Earth and inside the laboratory "CZ" where the reaction is being conducted. The effect of gravity "M87" on the rate constant of this gas-phase reaction conducted in the laboratory "CZ" and on the surface of Earth is elaborated in Table 1.

Table 1: Comparison of rate constants on the surface of the Earth's gravitational field and in the laboratory

Rate constant on the surface of Earth[41] (cm^3 molecule^{-1} s^{-1})	Rate constant of the reaction in "CZ" (cm^3 molecule^{-1} s^{-1})
0.92×10^{-11}	0.92×10^{-12}[a]

[a] This value is based on Eq. (74).

"CZ" was built at a distance of 939 km from the event horizon of the Black hole M87.

7.2 Rearrangement of *syn* and *anti*-aldehyde conformers to oxazole and ketene

To further elaborate the use of the current theory, we will consider the rearrangement of two conformers of the aldehyde to oxazole and ketene. The *syn* and *anti*-aldehyde conformers of triplet 2-formyl-3-fluorophenylnitrene generated in a nitrogen matrix by UV-irradiation of the azide precursor spontaneously rearrange to the corresponding 2,1-benzisoxazole and imino-ketene, respectively [43]. The rate constants for these transformations reported are 1×10^{-3} s^{-1} and 6×10^{-3} s^{-1} at 10 and 20 K [43]. If the same reactions are carried out at a height of 20,200 km from the surface of the Earth, keeping the temperature constant as that was on the surface of the Earth, *i.e.*, 10 and 20 K, respectively, then applying again Eq. (43) will give the rate constants to be $1.000000017 \times 10^{-3}$ s^{-1} and $6.000000101 \times 10^{-3}$ s^{-1}. Thus, the rate of the reaction has increased at a weaker gravitational field, *i.e.*, 20,200 km from the surface of the Earth. To study solely the effect of the gravitational field on the rate of the chemical reaction, all the external parameters that can affect the reaction rate, *i.e.*, temperature, volume, and pressure, should be kept the same at two gravitational potentials where reactions must be carried out. In the present case, theoretically, the temperature for both the reactions on the surface of Earth (stronger gravitational field) and at a height of 20,200 km from the surface of the Earth (weaker gravitational field) are kept the same, *i.e.*, 10 and 20 K, respectively.

8 Conclusions

All gravitational transformations developed in the current theory fully support the slower flow of time near the surface of heavy planets, which is one of the main experimentally verified facts of general relativity. The slower decay of excited states near the source of gravity is achieved by squeezing the spacing between the permitted quantum levels. This result has been proved mathematically to obtain the β-gravitational transformation of energy spacing. Thus, gravity seems to kill quantization. The behavior of gravitational force appears to be quantum-phobic, which tries to reduce the width of quantization. For heavy planets like Earth, this effect will not be large enough, but massive bodies like black holes will have a pronounced effect on the quantization. Gravity had already been reported to induce decoherence in micro-scale quantum systems and, therefore, account for the emergence of classicality [44]. The gravitational transformations of all thermodynamic state functions formulated in this study are completely compatible with gravitational time dilation. The rate constant of the reaction decreases near a stronger gravitational potential, which thus successfully explains the slowing down of the rate of all molecular processes near the source of gravity. Thus, slower time flow in molecular rate processes at stronger gravitational potential is a consequence of an increase in the mass of subatomic particles constituting atoms and molecules and a decrease in the energy spacing of all quantum levels associated with them.

Funding information: The author states no funding involved.

Author contribution: The author has accepted responsibility for the entire content of this manuscript and approved its submission.

Conflict of interest: The author states no conflict of interest.

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