Will there be future deceleration?—A study of particle creation mechanism in non-equilibrium thermodynamics

Supriya Pan and Subenoy Chakraborty

Department of Mathematics, Jadavpur University, Kolkata-700 032, India.

The paper deals with non-equilibrium thermodynamics based on particle creation mechanism with the motivation of considering it as an alternative choice to explain the recent observed accelerating phase of the universe. The particle creation mechanism results in a dissipative phenomenon which is essentially a bulk viscous pressure for homogeneous and isotropic flat FRW model of the universe. Also, this bulk viscous pressure depends linearly on the particle creation rate for adiabatic process. Further, using Friedmann equations, it is shown that the deceleration parameter can be obtained from the knowledge of the particle production rate ($\Gamma$). From thermodynamical point of view, the particle creation rate $\Gamma$ has been chosen as (i) $\Gamma \propto H^2$, (ii) $\Gamma \propto H$ and (iii) $\Gamma \propto \frac{1}{H}$ for early inflationary epoch, intermediate matter dominated era and late time accelerating phase respectively and cosmological solutions have been evaluated. The deceleration parameter is expressed as a function of the red shift parameter ($z$) and its variation is presented graphically. Finally, two non-interacting fluids with different particle creation rates are considered as cosmic substratum and deceleration parameter ($q$) is evaluated. It is examined whether more than one transition of $q$ is possible or not by graphical representations.

Keywords: Particle creation, evolution of the universe, deceleration parameter.

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a pansupriya051088@gmail.com
b schakraborty@math.jdvu.ac.in
I. INTRODUCTION

There was a dramatic change in our knowledge of the evolution history of the universe based on the standard cosmology at the end of the last century due to some observational predictions from type Ia Supernova [1, 2] and others [3, 4]. Riess et al [1] and Perlmutter et al [2] observed that distant supernovae at redshift $z \sim 0.5$ and $\Delta m \sim 0.25$ mag are found to be about 25% fainter than the prediction from standard cosmology and they concluded that the universe at present is undergoing through an accelerated expansion rather than deceleration (as predicted by the standard cosmology). This present accelerating phase was also supported by the Cosmic Microwave Background (CMB) [3] and Baryon Acoustic Oscillations (BAO) [4]. The explanation of this unexpected accelerating phase is a great challenge to the theoretical physics.

People are trying to explain this observational fact in two different ways– either modifying the Einstein’s gravity itself or by introducing some unknown kind of matter in the framework of Einstein gravity. In the second option normally, cosmological constant is the common choice for this unknown matter. But it suffers from two fold difficulties– the measured value of the cosmological constant is far below the prediction from quantum field theory and secondly the coincidence problem [5]. So, people choose this unknown matter as some kind of dynamical fluid with negative and time dependent equation of state and is termed as dark energy (DE). Though a lot of works have been done with several models of DE (see references [6-9] for reviews) but still its origin is totally mysterious.

The present work is an attempt to un revel this mysterious origin of the transitions of the deceleration parameter using non-equilibrium thermodynamics through the mechanism of particle creation. Among other possibilities to explain the present accelerating stage, inclusion of backreaction in the Einstein’s field equations through an (-ve) effective pressure is much relevant in the context of cosmology and the gravitational production of particles [radiation or cold dark matter (CDM)] provides a mechanism for cosmic acceleration [10-13]. In particular, in comparison with DE models the particle creation scenario has a strong physical basis- non-equilibrium thermodynamics. Also the particle creation mechanism not only unifies the dark sectors (DE+DM) [13] but also it contains only one free parameter as we need only a single dark component (DM). Further, Statistical Bayesian analysis with one free parameter should be preferred along with the hierarchy of cosmological models [14]. So the present particle creation model which simultaneously fits the observational data and alleviates the coincidence and fine-tuning problems, is better compared to the known (one-parameter) models namely (i) the concordance $\Lambda$CDM which however suffers from the coincidence and fine-tuning problems [15-
and (ii) the brane world cosmology [18] which does not fit the SNIa+BAO+CMB(shift-parameter) data [19].

The homogeneous and isotropic flat FRW model of the universe is chosen as an open thermodynamics system which is adiabatic in nature. Although the entropy per particle is constant for this system, still there is entropy production due to expansion of the universe (i.e., enlargement of the phase space) [20]. As a result, the dissipative pressure (i.e., bulk viscous pressure) is linearly related to the particle creation rate $\Gamma$ [20, 21]. Further, using the Friedmann equations one can relate $\Gamma$ to the evolution of the universe [see equation (8) below]. Choosing $\Gamma$ as a function of the Hubble parameter from thermodynamical view point, it is possible to describe different phases of the evolution of the universe and $q$ can be obtained as a function of $z$, the red shift parameter. Finally, we consider two components of matter which have different particle creation rate [22] and $q$ has been evaluated and plotted to examine whether more than one transition of $q$ is possible or not. The paper is organized as follows: section II deals with non-equilibrium thermodynamics in the background of particle creation mechanics while several choices of $\Gamma$ as a function of the Hubble parameter are shown in section III and the deceleration parameter $q$ has been presented both analytically and graphically. A field theoretic analysis of the particle creation mechanism is presented in section IV. Section IV is related to interacting two dark fluids having different particle creation rates and it is examined whether two transitions for $q$ are possible or not. Finally, there is a summary of the work in section VI.

II. NON EQUILIBRIUM THERMODYNAMICS: MECHANISM OF PARTICLE CREATION

Suppose the homogeneous and isotropic flat FRW model of the universe is chosen as an open thermodynamical system. The metric ansatz takes the form

$$dS^2 = -dt^2 + a^2(t)[dr^2 + r^2d\Omega^2]$$ (1)

Then the Friedmann equations are

$$3H^2 = \kappa\rho \quad and \quad 2\dot{H} = -\kappa(\rho + p + \Pi).$$ (2)

where, $\rho$ and $p$ are the energy density and the thermodynamical pressure of the cosmic fluid and $\Pi$ is related to some dissipative phenomena (bulk viscous pressure). The energy conservation relation reads
\[ \dot{\rho} + 3H(\rho + p + \Pi) = 0. \] (3)

As the particle number is not conserved (i.e., \( N_{\mu}^\mu \neq 0 \)), so the modified particle number conservation equation takes the form [22]

\[ \dot{n} + \Theta n = n\Gamma, \] (4)

where, \( n = \frac{N}{V} \) is the particle number density, \( N \) is the total number of particles in a comoving volume \( V \), \( N^\mu = nu^\mu \) is the particle flow vector, \( u^\mu \) is the particle velocity, \( \Theta = \eta_{\mu}^\mu \) stands for fluid expansion, \( \Gamma \) represents the particle creation rate and notationally, \( \dot{n} = \eta_{\mu}^\mu u^\mu \). The sign of \( \Gamma \) indicates creation (for \( \Gamma > 0 \)) or annihilation (for \( \Gamma < 0 \)) of particles and \( \Gamma \) represents some dissipative effect to the cosmic fluid so that non-equilibrium thermodynamics comes into picture.

Now, from the Gibb’s equation using Clausius relation we have [22]

\[ Tds = d(\rho/n) + pd(1/n), \] (5)

where, ‘s’ represents entropy per particle and \( T \) is the fluid temperature. Using the conservation relations (3) and (4), the variation of entropy can be expressed as [20, 21]

\[ nT\dot{s} = -\Pi\Theta - \Gamma(\rho + p). \] (6)

Further, for simplicity if we assume the thermal process to be adiabatic (i.e., \( \dot{s} = 0 \)), then from equation (6) we have [20, 21]

\[ \Pi = -\frac{\Gamma}{\Theta}(\rho + p). \] (7)

Thus, dissipative pressure is completely characterized by the particle creation rate for the above simple (isentropic) thermodynamical system. In other words, the cosmic substratum may be considered as perfect fluid with barotropic equation of state, \( p = (\gamma - 1)\rho \) and dissipative phenomena comes into picture through particle creation. Further, although the entropy per particle is constant but still there is entropy generation due to particle creation, i.e., enlargement of the phase space through expansion of the universe. So, in a sense the non-equilibrium configuration is not the conventional
one due to the effective bulk pressure, rather a state with equilibrium properties as well (but not the equilibrium era with \( \Gamma = 0 \)). Now eliminating \( \rho \), \( p \) and \( \Pi \) from the Einstein field equations (2) and the isentropic condition (7) using barotropic equation of state, \( \gamma = 1 + \frac{p}{\rho} \), we obtain [20, 21]

\[
\frac{\Gamma}{\Theta} = 1 + \frac{2}{3\gamma} \frac{\dot{H}}{H^2}.
\] (8)

which shows that in case of adiabatic process the particle creation rate is related to the evolution of the universe.

III. PARTICLE CREATION RATE AS A FUNCTION OF THE HUBBLE PARAMETER AND EVOLUTION OF THE UNIVERSE

Introducing the deceleration parameter

\[
q = -(1 + \frac{\dot{H}}{H^2});
\] (9)

and using equation (8) we have

\[
q = -1 + \frac{3\gamma}{2}(1 - \frac{\Gamma}{\Theta}).
\] (10)

In the following subsections we shall choose \( \Gamma \) as different functions of the Hubble parameter to describe different stages of evolution of the universe and examine whether \( q \) so obtained from equation (10) has any transition (from deceleration to acceleration or vice versa) or not.

A. Early epochs

In the very early universe (starting from a regular vacuum) most of the particle creation effectively takes place and from thermodynamic point of view we have [23]

\( \text{(i) At the beginning of the expansion, there should be maximal entropy production rate (i.e., maximal particle creation rate) so that universe evolves from non-equilibrium thermodynamical state to equilibrium era with the expansion of the universe.} \)

\( \text{(ii) A regular (true) vacuum for radiation initially, i.e., } \rho \rightarrow 0 \text{ as } a \rightarrow 0. \)
(iii) $\Gamma > H$ in the very early universe so that the created radiation behaves as thermalized heat bath and subsequently, the creation rate should fall slower than expansion rate and particle creation becomes dynamically insignificant.

Now, according to Gunzig et al. [24], the simplest choice satisfying the above requirements is that particle creation rate is proportional to the energy density, i.e., $\Gamma = \Gamma_0 H^2$, $\Gamma_0$ is a proportionality constant.

For this choice of $\Gamma$, $H$ can be solved from (8) as [21]

$$H = \frac{H_r}{\beta + (1 - \beta)(\frac{a}{a_r})^{3\gamma/2}}, \tag{11}$$

where, $\beta$ is related to $\Gamma_0$ as $\Gamma_0 = \frac{3\beta}{H_r}$. $H_r$ and $a_r$ are chosen to be the values of the Hubble parameter and the scale factor at some instant. We note that as $a \to 0, H \to \beta^{-1} H_r = constant$, indicating an exponential expansion ($\ddot{a} > 0$) in the inflationary era, while for $a \gg a_r$, $H \propto a^{-\frac{3\gamma}{2}}$, indicates the standard FRW cosmology ($\ddot{a} < 0$). So, if we identify $"a_r"$ at some intermediate value of 'a', where, $\ddot{a} = 0$, i.e., a transition from de Sitter accelerating phase to the standard decelerating radiation phase, then we have $\dot{H}_r = -H_r^2$ and the equation (8) gives [21]

$$\beta = 1 - \frac{2}{3\gamma}. \tag{12}$$

Now using (10) we obtain

$$q(z) = -1 + \frac{3\gamma}{2} \left[ 1 - \frac{\beta}{\beta + (1 - \beta)(1 + z)^{-3\gamma/2}} \right]. \tag{13}$$

where, the red shift parameter $z$ is defined as, $\frac{a}{a_r} = 1 + z$. Figure 1 shows that the transition of the deceleration parameter $q(z)$ from early inflationary era to the decelerated radiation era.

B. Intermediate decelerating phase

Here the simple natural choice is $\Gamma \propto H$. It should be noted that this choice of $\Gamma$ does not satisfy the third thermodynamical requirement (mentioned above) at the early universe. Also the solution will not satisfy the above condition (ii) of Case I.

In this case $q$ does not depend on expansion rate, it only depends on $\gamma$. For radiation (i.e., $\gamma = 4/3$)
Figure 1 shows the transition of the 
deceleration parameter \( q \) [see Eqn. (13)] 
from acceleration to deceleration in the 
early phase.

Figure 2 shows the transition of the 
deceleration parameter \( q \) [see Eqn. (15)] 
from deceleration to recent accelerating 
phase.

\[ q = 1 - \frac{2\Gamma_1}{3}, \]  

while for matter dominated era (i.e., \( \gamma = 1 \)) \( q = \frac{1}{2} - \frac{\Gamma_1}{2} \). So, if \( \Gamma_1 < 1 \), then we have 
deceleration in both the epochs as in standard cosmology while there will be acceleration if \( \Gamma_1 > \left(3 - \frac{2}{\gamma}\right)\).

The solution for the Hubble parameter and the scale factor are given by

\[ H^{-1} = \frac{3\gamma}{2} (1 - \Gamma_0) t \]

and

\[ a = a_0 t^l \]

where, \( l = \frac{2}{3\gamma(1 - \Gamma_0)} \), which is the usual power law expansion of the universe in standard cosmology with particle production rate decreases as \( t^{-1} \).

C. Late time evolution: Accelerated expansion

In this case the thermodynamical requirements of Case I are modified as [24]

(i) There should be minimum entropy production rate at the beginning of the late time accelerated expansion and the universe again becomes non-equilibrium thermodynamically.
(ii) The late time false vacuum should have $\rho \rightarrow 0$ as $a \rightarrow \infty$.

(iii) The creation rate should be faster than the expansion rate.

We shall show that another simple choice of $\Gamma$, namely, $\Gamma \propto \frac{1}{H}$, i.e., $\Gamma = \frac{\Gamma_3}{H}$, where, $\Gamma_3$ is a proportionality constant, will satisfy these requirements.

For this choice of $\Gamma$, the Hubble parameter is related to the scale factor as [21]

$$H^2 = \frac{\Gamma_3}{3} + \left(\frac{a}{a_f}\right)^{-3\gamma},$$

(14)

where, $a_f$ is some intermediate value of $'a'$ such that

$$H \sim a^{-\frac{3\gamma}{2}} \quad \text{for} \quad a \ll a_f$$

$$H \sim \frac{\Gamma_3}{3} \quad \text{for} \quad a \gg a_f$$

So, we have a transition from the standard cosmological era ($\ddot{a} < 0$) to late time acceleration ($\ddot{a} > 0$) and $a_f$'s can be identified as the value of the scale factor at the instant of transition ($\ddot{a} = 0$).

The deceleration parameter now has the expression

$$q = -1 + \frac{3\gamma}{2} \left[ \frac{1}{1 + \left(\frac{\Gamma_3}{3}\right)(1 + z)^{-\frac{3\gamma}{2}}} \right],$$

(15)

where, the redshift parameter is defined in this case as $\frac{a_f}{a} = 1 + z$. The graphical representation of $q(z)$ in figure 2 shows the transition of the universe from matter dominated era to present late time acceleration.

IV. FIELD THEORETIC ANALYSIS AND PARTICLE CREATION

This section deals with particle creation from vacuum using quantum field theory [25]. In particular, the quantum effect of particle creation is considered in the context of thermodynamics of open
systems and is interpreted as an additional negative pressure.

The energy-momentum tensor corresponding to the quantum vacuum energy is

\[ T_{\mu\nu}^Q \equiv \langle T_{\mu\nu}^Q \rangle = \Lambda(t)g_{\mu\nu}. \]

So the energy conservation equation of a perfect fluid is now modified as

\[ \dot{\rho} + 3H(p + \rho) = -\dot{\Lambda}, \tag{16} \]

which shows an energy transfer from the decaying vacuum to matter. This modified energy conservation equation can be considered as the energy balance equation for an imperfect fluid with bulk viscous pressure

\[ \Pi = \frac{\dot{\Lambda}}{3H}. \]

Now, if the perfect fluid is considered as a scalar field with potential \( V(\phi) \), i.e.,

\[ \rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi), \quad p_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi) \]

Then the Einstein’s field equations become

\[ 3H^2 = \frac{1}{2}\dot{\phi}^2 + V(\phi) + \Lambda(t), \quad 2\dot{H} + 3H^2 = -\frac{1}{2}\dot{\phi}^2 + V(\phi) + \Lambda(t). \tag{17} \]

and the evolution equation of the scalar field is given by

\[ \ddot{\phi} + \dot{\phi} \frac{dV}{d\phi} + 3H(\dot{\phi}^2 + \frac{\dot{\Lambda}}{3H}). \tag{18} \]

So we have,

\[ \phi = \int \sqrt{-\frac{2H'}{aH}} \quad \text{and} \quad V = -\Lambda + 3H^2 \left[ 1 + \frac{aH'}{3H} \right]. \tag{19} \]

where, ‘\( ' \) stands for the differentiation with respect to the scale factor \( a \). Hence, for adiabatic process the particle creation rate can be written as

\[ \Gamma = \frac{H}{2(1 + q)} \left[ (4 - r) + \frac{1}{H^3} \frac{dV}{d\phi} \sqrt{-2\dot{H}} \right]. \tag{20} \]

where, \( r = \frac{\dot{a}}{aH^2} \) is the statefinder parameter and \( q = -(1 + \frac{\dot{H}}{H^2}) \) is the usual deceleration parameter.
Figure 3 is a comparative study of the deceleration parameter ($q$) with the Hubble parameter ($H$) for different particle creation rates ($\Gamma$) for the set of values $\Omega_1 = 0.4$, $\Omega_2 = 0.6$, $\omega_1 = 0.1$ and $\omega_2 = 0.4$. The figure describes from inflation to late time acceleration.

Figure 4 shows the variation of the deceleration parameter ($q$) with the Hubble parameter ($H$) in different equation of states for the following unequal particle creation rates, $\Gamma_1 = H^2$ and $\Gamma_2 = \frac{1}{H}$ for $\Omega_1 = 0.4$, $\Omega_2 = 0.6$. From inflation to late time acceleration is described by this figure.

Figure 5 is interesting because it indicates that perhaps there would be another transition from the recent accelerating phase to the decelerating phase with $\Gamma_1 \approx 0.12 H^2$ and $\Gamma_2 \approx \frac{20.71}{H^2}$.18.
V. TWO NON-INTERACTING FLUIDS AS COSMIC SUBSTRATUM AND PARTICLE CREATIONS

In this section, we suppose that the present open thermodynamical system contains two non-interacting fluids dark which have different particle creation rates. Let, \((\rho_1, p_1)\) and \((\rho_2, p_2)\) are the energy density and thermodynamic pressure of the fluids respectively. Suppose \((n_1, n_2)\) denote the number density of the two fluids having balance equations [22]

\[
\dot{n}_1 + 3Hn_1 = \Gamma_1 n_1 \quad \text{and} \quad \dot{n}_2 + 3Hn_2 = -\Gamma_2 n_2. \tag{21}
\]

where, \(\Gamma_1 > 0\) and \(\Gamma_2 > 0\). The above equations imply that there is creation of particles of fluid-1, while, particles of fluid-2 decay. Now, combining equations in (17), the total number of particles \(n = n_1 + n_2\) will have the balance equation

\[
\dot{n} + 3Hn = \left(\frac{\Gamma_1 n_1 - \Gamma_2 n_2}{n}\right)n = \Gamma n. \tag{22}
\]

So, the total number of particles will remain conserve, if \(\Gamma = 0\), i.e., \(\Gamma_1 n_1 = \Gamma_2 n_2\)

Again from the isentropic condition (7), the dissipative (bulk) pressure of the matter components are given by

\[
\Pi_1 = -\frac{\Gamma_1}{3H}(\rho_1 + p_1) \quad \text{and} \quad \Pi_2 = -\frac{\Gamma_2}{3H}(\rho_2 + p_2). \tag{23}
\]

As a consequence, the energy conservation relations are

\[
\dot{\rho}_1 + 3H(\rho_1 + p_1) = \Gamma_1(\rho_1 + p_1) \quad \text{and} \quad \dot{\rho}_1 + 3H(\rho_1 + p_1) = -\Gamma_2(\rho_2 + p_2). \tag{24}
\]

Now, if \(\omega_1 = \frac{p_1}{\rho_1}\) and \(\omega_2 = \frac{p_2}{\rho_2}\) are the equations of state of the two fluid components respectively, then from the above two conservation relations the effective equation of state parameters are

\[
w_1^{eff} = \omega_1 - \frac{\Gamma_1}{3H}(1 + \omega_1) \quad \text{and} \quad w_2^{eff} = \omega_2 + \frac{\Gamma_2}{3H}(1 + \omega_2). \tag{25}
\]

Thus from the Einstein’s equations we have

\[
3H^2 = \rho_1 + \rho_2 \quad \text{and} \quad 2\dot{H} = -\left[(\rho_1 + p_1 + \Pi_1) + (\rho_2 + p_2 + \Pi_2)\right]. \tag{26}
\]
Figure 6 describes our universe from inflation to late time acceleration for the equal particle creation rate, \( \Gamma = 2H^2 + \frac{3}{H} \).
We take, \( \Omega_1 = 0.6 \) and \( \Omega_2 = 0.4 \).

Figure 7 shows the evolution of the universe from the inflation to late-time acceleration for the particle creation rate \( \Gamma = 2H^2 + 1 \).
Parameters taken, \( \Omega_1 = 0.6, \Omega_2 = 0.4 \).

Figure 8 also reflects the possible future deceleration just as we have the future deceleration in case of unequal particle creation rate, where, \( \Gamma \approx 0.34 \)

\[
H^2 \cdot \frac{18.18}{H} + 18.69.
\]

Then the deceleration parameter can be written as [26]

\[
q = \frac{1}{2} + \frac{3}{2} \left[ -\frac{\Gamma_1}{3H} \Omega_1 (1 + \omega_1) + \frac{\Gamma_2}{3H} \Omega_2 (1 + \omega_2) + (\Omega_1 \omega_1 + \Omega_2 \omega_2) \right].
\]  

(27)

In particular, if \( \Gamma_1 = \Gamma_2 = \Gamma (\text{say}) \), then the above form of the deceleration parameter \( q \) reads
\[ q = \frac{1}{2} + \frac{3}{2} \left( \Omega_1 \omega_1 + \Omega_2 \omega_2 \right) + \frac{\Gamma}{3H} \left( \Omega_2 \omega_2 - \Omega_1 \omega_1 + (\Omega_2 - \Omega_1) \right) \]  

(28)

We have shown graphically in Figures 3-8, how the deceleration parameter behaves with the Hubble parameter for different choices of the particle creation rate (equal or unequal) and we see here that, it also matches with the present observations.

VI. SUMMARY OF THE WORK

The present work deals with non-equilibrium thermodynamics from the point of view of particle creation formalism. In the context of universal thermodynamics, flat FRW model of the universe is considered as the open thermodynamical system. Although, cosmic fluid is chosen in the form of the perfect fluid, but dissipative effect in the form of bulk viscous pressure arises due to particle production mechanism. For simplicity of calculations, we are restricted to the adiabatic process where the dissipative pressure is linearly related to the particle production rate (\( \Gamma \)). From thermodynamic point of view, \( \Gamma \) is chosen as a function of the Hubble parameter (\( H \)) and the deceleration parameter is shown to be a function of the red shift parameter. In particular, by proper choices of \( \Gamma \), cosmological solutions are evaluated and the deceleration parameter is presented graphically in figures 1 and 2. The graphs show a transition from early inflationary era to radiation (Figure 1) and also the transition from matter dominated era to the present late time acceleration (Figure 2). Then a field theoretic analysis has been shown for the particle creation mechanism in section IV. Finally, in section V, a combination of non-interacting two perfect fluids having different particle creation rate is considered as a cosmic substratum and deceleration parameter is evaluated. The behaviour of the deceleration parameter is examined graphically in figures 3-8. Figures 3, 4, 6 and 7 show two transitions of \( q \)-one in the early epoch from acceleration to deceleration and the other one corresponds to transition in the recent past from deceleration to present accelerating phase. The figures 3 and 4 correspond to two different choices of unequal particle creation parameters while for two distinct equal particle creation rate, the variation of \( q \) are presented in figures 6 and 7. There are three distinct transitions of \( q \) for unequal and equal particle creation parameters in figures 5 and 8 respectively. Both the figures predict a future transition to decelerating era again. Thus theoretically, considering non-interacting two fluid system as cosmic substratum, it is possible to have again a decelerating phase of the universe in future. Therefore, we may conclude that the present observed accelerating phase is due to non-equilibrium thermodynamics having particle creation process or in otherwords, in addition to the presently known two possibilities (namely, modification of Einstein gravity or introduction of some
unknown exotic fluid, i.e., DE) for explaining the recent observations, non-equilibrium thermodynamics through particle creation mechanism may explain not only the late time acceleration but also exhibits early inflationary scenario and predict future transition to decelerating era again.

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