In this paper, we regard dilaton in Weyl-scaled induced gravitational theory as coupled Quintessence, which is called DCQ model by us. Parametrization of the dark energy model is a good method by which we can construct the scalar potential directly from the effective equation of state function \( \omega(\sigma) \) describing the properties of the dark energy. Applying this method to the DCQ model, we consider four parametrizations of \( \omega(\sigma) \) and investigate the features of the constructed DCQ potentials, which possess two different evolutive behaviors called "O" mode and "E" mode. Lastly, we comprise the results of the constructed DCQ model with those of quintessence model numerically.

**Keywords:** Dark energy; Dilaton; Coupled Quintessence; Parametrization; Potential.

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1. Introduction

Data of high-redshift Type Ia Supernova[1] and the Cosmic Microwave Background[2] have shown us such a fact: the density of clustered matter including cold dark matters plus baryons, \( \Omega_m \approx 0.3 \), and that the Universe is flat to high precision, \( \Omega_{\text{total}} = 0.99 \pm 0.03 [3] \). That is to say, we are living in a flat universe which is undergoing a phase of accelerated expansion, and there exists an unclumped form of energy density pervading the Universe. This unknown energy density which is called "dark energy" with negative pressure, contributes to two thirds of the total energy density. To know the nature of dark energy is one of the most challengeable problems in cosmological research. So far, theoretical physicists and astrophysicists have constructed many models including cosmological constant \( \Lambda \), Quintessence[4-14], K-essence[15], Tachyon[16], Phantom[17-20], Quintom[21] and holographic dark energy[22] so on, to fit these observations. Perhaps the simplest explanation for these data is that the dark energy corresponds to a positive cosmological constant. However, the cosmological constant model suffers from two serious issues called "coincidence problem" and "fine-tuning problem". The essential characteristics of these dark energy models are contained in the parameter of its equation of state, \( p = \omega \rho \), where \( p \) and \( \rho \) denote the pressure and energy density of dark energy, respectively, and \( \omega \) is a state parameter. Quintessence model has been widely studied, and its state parameter \( \omega_0 \) which is time-dependent, is greater than \(-1\). Such a model for a broad class of potentials can give the energy density converging to its present value for a wide set of initial conditions in the past and posses tracker behavior. The quintessence potential \( V(\phi) \) and the equation of state \( \omega_0(z) \) may be reconstructed from supernova observations[23]. Guo et al.[24] have constructed a theoretical method of constructing the quintessence potential \( V(\phi) \) directly from the dark energy equation of state function \( \omega_0(z) \). They investigated the general features of quintessence potentials and obtained that the typical behavior of the potentials is a runaway type.

In this paper, we regard dilaton in Weyl-scaled induced gravitational theory as a coupled Quintessence[25]. We call our model DCQ model. We apply the theoretical method of parametrization of dark energy to the DCQ model and consider four typical parametrization of \( \omega_0(z) \) as follows[26-31]: Case I: \( \omega_0 = \omega_0 \); Case II: \( \omega_0 = \omega_0 + \omega_1 z \); Case III: \( \omega_0 = \omega_0 + \omega_1 \ln(1 + z) \), which fit the observations well. In these four cases, the properties of the constructed DCQ potentials \( W_\sigma(z) \) are considered and the evolutions of the dark energy density \( \rho_\sigma(z) \) with respect to \( z \) are also shown mathematically.

2. Basic Equations
Now let us consider the action of the Weyl-scaled induced gravitational theory:

\[ S = \int d^4 X \sqrt{-g} \left[ \frac{1}{2} R(g_{\mu\nu}) - \frac{1}{2} g^{\mu\nu} \partial_\mu \sigma \partial_\nu \sigma - W(\sigma) + L_{\text{fluid}}(\psi) \right] \]  \tag{1}

where the lagrangian density of cosmic fluid \( L_{\text{fluid}}(\psi) = \frac{1}{2g} g^{\mu\nu} e^{-\alpha \sigma} \partial_\mu \psi \partial_\nu \psi - e^{-2\alpha \sigma} V(\psi) \), \( \alpha = \sqrt{\kappa^2 / (2\pi) + \frac{3}{2}} \) with \( \kappa \sim 3500[32] \) being an important parameter in Weyl-scaled induced gravitational theory, \( \sigma \) is DCQ potential, \( W(\sigma) \) is DCQ potential, \( g_{\mu\nu} \) is the Pauli metric which can really represent the massless spin-two graviton and should be considered to be physical metric[33]. This means that, as long as one wants to interpret the theory as a generalization of Einstein’s theory, one must treat the Pauli metric as physical. In the Kaluza-klein theory Cho also arrives essentially at the same conclusion, but for a different reason. One cannot treat the Jordan metric as physical, because it violates the positivity of the Hamiltonian. At the same time, one must accept the Pauli metric as physical, as long as one wishes to achieve the unification of Einstein’s gravitation with other interactions from the Kaluza-Klein theory. We work in units (\( \kappa^2 \equiv 8\pi G = 1 \)). From the solar system tests, the current constrain is \( \alpha^2 < 0.001[34] \). The new constrain on the parameter is \( \alpha^2 < 0.0001[35] \), which seems to argue against the existence of long-range scalars. Perhaps such a pessimistic interpretation of the limit is premature [33,34]. The conventional Einstein gravity limit occurs as \( \sigma \to 0 \) for an arbitrary \( \varpi \) or \( \varpi \to \infty \) with an arbitrary \( \sigma \). When \( W(\sigma) = 0 \), it will result in the Einstein-Brans-Dicke theory.

By varying action (1) and working in FRW universe, we obtain the field equations of Weyl-scaled induced gravitational theory:

\[ H^2 = \frac{1}{3}[\rho_\sigma + e^{-\alpha \sigma} \rho] \]  \tag{2}

\[ \frac{\dot{a}}{a} = -\frac{1}{6}(e^{-\alpha \sigma} \rho + \rho_\sigma + p_\sigma) \]  \tag{3}

\[ \dot{\sigma} + 3H \dot{\sigma} + \frac{dW(\sigma)}{\sigma} = \frac{1}{2}\alpha e^{-\alpha \sigma} (\rho - 3p) \]  \tag{4}

\[ \dot{\rho} + 3H (\rho + p) = \frac{1}{\alpha} \dot{\sigma} (\rho + 3p) \]  \tag{5}

where \( H = \frac{\dot{a}}{a} \) is Hubble parameter, and \( \rho \) includes matter energy density \( \rho_m \) and the radiation energy density \( \rho_r \). In what follows, we shall neglect the radiation energy density \( \rho_r \). For matter \( \rho_m = 0 \), we get \( \rho_m = \frac{3\rho}{a^3} \) from Eq.(5). The effective energy density \( \rho_\sigma \) and the effective pressure \( p_\sigma \) of DCQ field can be expressed as follows

\[ \rho_\sigma = \frac{1}{2} \dot{\sigma}^2 + W(\sigma) \]  \tag{6}

\[ p_\sigma = \frac{1}{2} \dot{\sigma}^2 - W(\sigma) \]  \tag{7}

According to the above results, we have

\[ W(\sigma) = 3H^2 + \dot{H} - \frac{1}{2} \rho_m e^{-\frac{2}{3} \alpha \sigma} a^{-3} \]  \tag{8}

\[ \dot{\sigma}^2 = -2\dot{H} - \rho_m e^{-\frac{2}{3} \alpha \sigma} a^{-3} \]  \tag{9}

The relationship between scale factor \( a \) and redshift \( z \) is \( z + 1 = \frac{a_0}{a} \) where \( a_0 \) denotes the value of scale factor at redshift \( z = 0 \)(present). So, we have

\[ \dot{H} = \frac{dH}{dt} = \frac{\frac{\dot{a}}{a} H}{\frac{\dot{a}}{a_0} \frac{a}{a_0}} \frac{dH}{dz} = -H(z + 1) \frac{dH}{dz} \]  \tag{10}

\[ \frac{\dot{a}}{a} = \frac{d\sigma}{dt} = -H(z + 1) \frac{d\sigma}{dz} \]  \tag{11}

Eqs.(8)(9) can be rewritten as

\[ W(z) = 3H^2 - H(z + 1) \frac{dH}{dz} - \frac{1}{2} \rho_m e^{-\frac{2}{3} \alpha \sigma} (1 + z)^3 \]  \tag{12}

\[ \dot{\sigma}^2 = \frac{2}{H(z + 1) \frac{dH}{dz}} - \frac{\rho_m e^{-\frac{2}{3} \alpha \sigma}}{H^2} (1 + z) \]  \tag{13}
We define the dimensionless dark energy function $\xi(z)$ as follows

$$\xi(z) = \frac{\rho_\sigma}{\rho_{\sigma_0}}$$ (14)

where $\rho_{\sigma_0}$ is dark energy density at redshift $z = 0$ (present). Using Eqs. (2)(14), we get

$$\frac{dH}{dz} = \frac{\rho_{\sigma_0}}{6H} \frac{d\xi}{dz} + \rho_{m_0} e^{-\frac{4}{3} \alpha \sigma (1 + z)^2} - \frac{\alpha \rho_{m_0} e^{-\frac{2}{3} \alpha \sigma (1 + z)^3}}{12H} \frac{d\sigma}{dz}$$ (15)

Substituting Eqs. (2)(15) into Eqs. (12)(13), we have

$$\tilde{W}(z) = (1 - \Omega_{m_0}) \left[ \xi(z) - \frac{1 + z}{6} \frac{d\xi}{dz} \right] + \frac{1}{12} \alpha \Omega_{m_0} e^{-\frac{2}{3} \alpha \sigma (1 + z)^3} \frac{d\sigma}{dz}$$ (16)

$$\frac{d\sigma}{dz} = -\frac{1}{\chi(z)} \left[ \frac{1 - \Omega_{m_0} (1 + z)}{1 + z} \frac{d\xi}{dz} - \frac{1}{2} \alpha \Omega_{m_0} e^{-\frac{2}{3} \alpha \sigma (1 + z)^3} \left( 1 + z \right)^2 \frac{d\sigma}{dz} \right]^\frac{1}{2}$$ (17)

where $\Omega_{m_0} \equiv \frac{\rho_{m_0}}{\rho_0}$ is the present matter energy density, with $\rho_0 = \rho_{\sigma_0} + \rho_{m_0}$ being present total energy density, $\tilde{W}(z) = W(z)/\rho_0$, and

$$\chi(z) = [(1 - \Omega_{m_0}) \xi(z) + \Omega_{m_0} e^{-\frac{2}{3} \alpha \sigma (1 + z)^3}]^\frac{1}{2}$$ (18)

is the cosmic expansion rate relative to its present value. From Eqs. (16)(17), we can see that the DCQ model will reduce to ordinary quintessence model as the coupled constant $\alpha \to 0$. Obviously, Eq. (17) is a nonlinear first-order differential equation with respect to $z$ and it is difficult to find its analytic solutions. Next we investigate the properties of the constructed DCQ potential numerically. In DCQ model, we take the simplest dimension dark energy function $\xi(z) = (1 + z)^{3(1 + \omega_\sigma)}$. So, Eqs. (16)(17) can be rewritten as

$$\tilde{W}(z) = \frac{1}{2} (1 - \Omega_{m_0}) (1 - \omega_\sigma) (1 + z)^{3(1 + \omega_\sigma)} + \frac{1}{12} \alpha \Omega_{m_0} e^{-\frac{2}{3} \alpha \sigma (1 + z)^3} (1 + z)^4 \frac{d\sigma}{dz}$$ (19)

$$\frac{d\sigma}{dz} = -\frac{1}{\chi(z)} \left[ 3 (1 - \Omega_{m_0}) (1 - \omega_\sigma) (1 + z)^{3(1 + \omega_\sigma)^2} - \frac{1}{3} \alpha \Omega_{m_0} e^{-\frac{2}{3} \alpha \sigma (1 + z)^3} (1 + z)^2 \left( 1 + z \right)^2 \frac{d\sigma}{dz} \right]^\frac{1}{2}$$ (20)

where $\chi(z) = [(1 - \Omega_{m_0}) (1 + z)^{3(1 + \omega_\sigma)} + \Omega_{m_0} e^{-\frac{2}{3} \alpha \sigma (1 + z)^3}]^\frac{1}{2}$. According Eqs. (19)(20), we can construct the DCQ potential directly. In fact the constant $\alpha$ reflects the coupled intensity. When the coupled constant $\alpha \to 0$, DCQ model will reduce to quintessence model and Eqs. (19)(20) become respective

$$\tilde{W}(z) = \frac{1}{2} (1 - \Omega_{m_0}) (1 - \omega_\sigma) (1 + z)^{3(1 + \omega_\sigma)}$$ (21)

$$\frac{d\sigma}{dz} = -\frac{1}{\chi(z)} \left[ 3 (1 - \Omega_{m_0}) (1 - \omega_\sigma) (1 + z)^{3(1 + \omega_\sigma)^2} - 2 \alpha \Omega_{m_0} e^{-\frac{2}{3} \alpha \sigma (1 + z)^3} (1 + z)^2 \left( 1 + z \right)^2 \frac{d\sigma}{dz} \right]^\frac{1}{2}$$ (22)

3. Specific Cases

Now let us consider four cases[26-31]of the $\omega_\sigma(z)$ in DCQ model, which fit the observations well.

Case I: $\omega_\sigma = \omega_0 [26]$

$$\tilde{W}(z) = \frac{1}{2} (1 - \Omega_{m_0}) (1 - \omega_0) (1 + z)^{3(1 + \omega_0)} + \frac{1}{12} \alpha \Omega_{m_0} e^{-\frac{2}{3} \alpha \sigma (1 + z)^3} (1 + z)^4 \frac{d\sigma}{dz}$$ (23)

$$\frac{d\sigma}{dz} = -\frac{1}{\chi(z)} \left[ 3 (1 - \Omega_{m_0}) (1 - \omega_0) (1 + z)^{3(1 + \omega_0)^2} - \frac{1}{3} \alpha \Omega_{m_0} e^{-\frac{2}{3} \alpha \sigma (1 + z)^3} (1 + z)^2 \left( 1 + z \right)^2 \frac{d\sigma}{dz} \right]^\frac{1}{2}$$ (24)

Case II: $\omega_\sigma = \omega_0 + \omega_1 z [27]$}

$$\tilde{W}(z) = \frac{1}{2} (1 - \Omega_{m_0}) (1 - \omega_0 - \omega_1 z) (1 + z)^{3(1 + \omega_0 + \omega_1 z)} + \frac{1}{12} \alpha \Omega_{m_0} e^{-\frac{2}{3} \alpha \sigma (1 + z)^3} (1 + z)^4 \frac{d\sigma}{dz}$$ (25)

$$\frac{d\sigma}{dz} = -\frac{1}{\chi(z)} \left[ 3 (1 - \Omega_{m_0}) (1 - \omega_0 - \omega_1 z) (1 + z)^{3(1 + \omega_0 + \omega_1 z)^2} - 2 \alpha \Omega_{m_0} e^{-\frac{2}{3} \alpha \sigma (1 + z)^3} (1 + z)^2 \left( 1 + z \right)^2 \frac{d\sigma}{dz} \right]^\frac{1}{2}$$ (26)
Case III: \( \omega_\sigma = \omega_0 + \omega_1 \frac{z}{1+z} \) [28–30]

\[
\tilde{W}(z) = \frac{1}{2}(1-\Omega_{m_0})(1-\omega_0-\omega_1 \frac{z}{1+z})(1+z)^{3(1+\omega_0+\omega_1 \frac{z}{1+z})} + \frac{1}{12} \alpha \Omega_{m_0} e^{- \frac{1}{2} \alpha \sigma (1+z)} \frac{d\sigma}{dz} \tag{27}
\]

\[
\frac{d\sigma}{dz} = -\frac{1}{\chi(z)} \left\{ 3(1-\Omega_{m_0})(1-\omega_0-\omega_1 \ln(1+z))(1+z)^{3(1+\omega_0+\omega_1 \ln(1+z))} - \frac{1}{2} \alpha \Omega_{m_0} e^{- \frac{1}{2} \alpha \sigma (1+z)} \frac{d\sigma}{dz} \right\} \tag{28}
\]

Case IV: \( \omega_\sigma = \omega_0 + \omega_1 \ln(1+z) \) [31]

\[
\tilde{W}(z) = \frac{1}{2}(1-\Omega_{m_0})(1-\omega_0-\omega_1 \ln(1+z))(1+z)^{3(1+\omega_0+\omega_1 \ln(1+z))} + \frac{1}{12} \alpha \Omega_{m_0} e^{- \frac{1}{2} \alpha \sigma (1+z)} \frac{d\sigma}{dz} \tag{29}
\]

\[
\frac{d\sigma}{dz} = -\frac{1}{\chi(z)} \left\{ 3(1-\Omega_{m_0})(1-\omega_0-\omega_1 \ln(1+z))(1+z)^{3(1+\omega_0+\omega_1 \ln(1+z))} - \frac{1}{2} \alpha \Omega_{m_0} e^{- \frac{1}{2} \alpha \sigma (1+z)} \frac{d\sigma}{dz} \right\} \tag{30}
\]

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**Fig. 1** The evolution of the dark energy density \( \rho_\sigma \) with respect to \( z \) in the four cases in DCQ model. We set \( \alpha = 0.0005, \Omega_{m_0} = 0.3, \omega_0 = -0.8, \omega_1 = 0.1 \) and \( \sigma_0 = 0.8 \).

**Fig. 2** Constructed DCQ potential in the four cases. We set \( \alpha = 0.0005, \Omega_{m_0} = 0.3, \omega_0 = -0.8, \omega_1 = 0.1 \) and \( \sigma_0 = 0.8 \).

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**Fig. 3** The evolution of the dark energy density \( \rho_\sigma \) with respect to \( z \) in the four cases when the coupling between dilaton and matter is zero (\( \alpha = 0 \)).

**Fig. 4** Quintessence potential in the four cases when the coupling between dilaton and matter is zero (\( \alpha = 0 \)).

Fig. 1 shows the evolution of the dark energy density \( \rho_\sigma \) with respect to \( z \) in the four cases in DCQ model. We can see that the slope of \( \rho_\sigma \) with respect to \( z \) becomes more steeper and more from Case I, Case III, Case IV to Case II. However, \( \rho_\sigma \) in the four cases tends to be the same evolutive behavior in range of \( 0 < z < 1(0.422 < \sigma < 0.8) \) while they differ when the redshift \( z \) becomes large. The evolution of the constructed DCQ potential \( \tilde{W}(z) \) with respect to \( z \) is shown in Fig. 2. We can easily see that the shape of \( \tilde{W}(z) \) is uniform in the range of \( 0.422 < \sigma < 0.8(0 < z < 1) \) while they differ beyond this range. To show difference between the DCQ model and the quintessence model, we also plot the evolution of \( \rho_\sigma \) and the constructed potential when coupling term becomes zero (\( \alpha = 0 \)) in Figs. 3–4. Comprising Fig. 1 with Fig. 3, we know the evolution of \( \rho_\sigma \) with respect to \( z \) is hardly distinct between the DCQ model and the quintessence model. However the shape of DCQ potentials are quite different from those of the quintessence potentials as shown in Fig. 2 and Fig. 4. In Fig. 4, quintessence potentials are all in the form of runaway type [24], which is related to the supersymmetric theories and tachyons in superstring theories interestingly. However, in DCQ
model, the evolution of DCQ potential with respect to DCQ field is divided into two different modes called "O" mode and "E" mode, because of the existence of coupling term. We see that the "O" mode possesses evolutive behavior of runaway type, just like quintessence potentials. On the contrary, DCQ potential in "E" mode tends to be infinite when $\sigma \to \infty$, which results in an unstable dynamic system.

3. Conclusions

In this paper, we apply the method of constructing quintessence potential to the DCQ model. Based on this, we investigate the evolutive behavior of the dark energy density $\rho_\sigma$ with respect to $z$ and the constructed DCQ potential with respect to $\sigma$ in four cases of the equation of state $\omega(z)$, which fit the observations well. These results are shown mathematically in the plots. According to the comparison between the constructed DCQ potential and quintessence potential ($\alpha = 0$), we find that the shapes of the constructed DCQ potential quite different from the one of quintessence potential. DCQ potentials possess two different evolutive mode "O" and "E". DCQ potentials in the "E" mode will lead to an unstable dynamic system, so, "E" mode will be ruled out. DCQ potential in "O" mode belongs to the form of runaway type, which is related to the supersymmetric theories and tachyons in superstring theories interestingly[36].

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