Physics of the Dark Universe 14 (2016) 40–47

Contents lists available at ScienceDirect

Physics of the Dark Universe

journal homepage: www.elsevier.com/locate/dark

Symmetry breaking and onset of cosmic acceleration in scalar field models

H. Mohseni Sadjadi [a,*], M. Honardoost [b], H.R. Sepangi [b]

[a] Department of Physics, University of Tehran, Islamic Republic of Iran

[b] Department of Physics, Shahid Beheshti University, Islamic Republic of Iran

ARTICLE INFO

Article history:
Received 27 February 2016
Received in revised form
4 August 2016
Accepted 19 September 2016

Keywords:
Dark energy
Quintessence
Dark matter
Symmetry breaking

ABSTRACT

We propose a new scenario for the onset of positive acceleration of our Universe based on symmetry breaking in coupled dark energy scalar field model. In a symmetry breaking process where the scalar field rolls down its own potential, the potential reduction is not in favor of acceleration. In our model, when dark matter density becomes less than a critical value, the shape of the effective potential is changed and, the quintessence field climbs up along *its own potential* while rolls down the effective potential. We show that this procedure may establish the positivity of the potential required for the Universe to accelerate. In addition, we show that by choosing an appropriate interaction between dark sectors there is the possibility that the scalar field resides in a new vacuum giving rise to a positive cosmological constant which is responsible for a permanent late time acceleration.

1. Introduction

To explain the positive acceleration of the Universe in the present era many models have been introduced. The most simple and natural candidate for dark energy is a cosmological constant which was first introduced by Einstein to oppose gravitational attraction resulting in a static universe. This idea was abandoned after the Hubble discovery but resurfaced again later to describe the present acceleration of the Universe [1]. The cosmological constant compatible with observation is nearly 120 orders of magnitude less than what is obtained by considering vacuum energy in the standard particle physics framework with a cutoff at the Planck scale. Hence it is reasonable to consider it as a constant of nature [2]. In the cosmological constant model dark energy density is constant and the equation of state parameter of dark energy is always −1. This situation changes when dynamical dark energies are employed.

A natural and simple model for dynamical dark energy is the scalar field model [3]. In this type of models, the acceleration of the Universe depends on the potential considered for the scalar field. This is similar to scalar field models of the early universe when inflation occurs during slow roll for nearly flat potentials or during rapid oscillations for specific power law potentials [4]. Note that, due to the presence of dark and ordinary matter at late times the problem is not as straightforward as in the inflationary epoch [5]. An important specification of scalar field models is their usability in the phenomenon of symmetry breaking in particle physics, where the initial symmetric state becomes unstable and the system rolls down to a new vacuum, breaking the initial symmetry [6]. Through this formalism and in the context of dark energy models, when the system leaves its false vacuum and settles down to a true vacuum, the cosmological constant is reduced. This formalism with fine tuning of the initial conditions can be considered as a bridge connecting the large value of the cosmological constant in the early universe to its small value at late times [2].

In recent years some attempts have been made to relate the onset of the acceleration of the Universe to symmetry breaking in scalar field models. Inspired by [7] where the symmetry breaking were used to end the slow roll inflation, a hybrid quintessence model was introduced in [8]. In this model beside the dark energy scalar field, another scalar field is present whose evolution causes the symmetry to brake. In this framework, the Universe may experience an acceleration while the scalar field is rolling down the total potential and also when it settles to the new minimum, provided that an appropriate potential is chosen. The same model was used in [9] to describe the phantom divide line crossing. In [10], due to the special form of the coupling of matter and scalar field dark energy, an effective potential has been obtained such that when the matter energy density becomes less than a critical

* Corresponding author.
E-mail addresses: mohsenisad@ut.ac.ir (H. Mohseni Sadjadi), m_honardoost@sbu.ac.ir (M. Honardoost), hr-sepangi@sbu.ac.ir (H.R. Sepangi).

http://dx.doi.org/10.1016/j.dark.2016.09.004
2212-6864/

value (determined by the parameters of the model) the symmetry is broken; the scalar fields rolls down towards the minimum of the effective potential and acceleration begins. In this model, dubbed symmetron, the matter density plays the role of the trigger field in the hybrid model. The same model has also been used to study the onset of inflation [11]. In these models, the fields rolls down along its own potential as well as the effective potential at the same time. So if initially (before the symmetry breaking) the field resides at the extremum of the unbroken effective potential, the symmetry breaking which decreases the value of the potential and increases the kinetic energy, is not in favor of the positive acceleration. This issue will be explained more in the third section. The acceleration obtained via numerical methods in these models arises from a positive constant term which was initially included (implicitly or explicitly) in the potential and has nothing to do with the symmetry breaking. Indeed in these types of models the symmetry breaking may be rather used to end the acceleration or the inflation [7].

In this paper we introduce a new proposal for the onset of acceleration based on symmetry breaking in a scalar field dark energy model in a spatially flat Friedmann Robertson Walker space time. In our model, after the effective potential shape is changed, contrary to symmetron and hybrid models, the quintessence climbs over its own potential. This procedure may establish the positivity of the potential which is necessary for the acceleration of the Universe.

The organization of the paper is as follows: In the second section we derives the role of the scalar field potential in driving the acceleration of the Universe. Our arguments upon which we construct our model is based on this section. In the third section we briefly review two quintessence models in which the symmetry breaking forces the scalar field to descend its own potential: the hybrid and symmetron models.

In section four we introduce a new proposal for late time acceleration based on symmetry breaking where the scalar field climbs over its own potential while descending down along the effective potential after the effective potential shape is changed into the form dictated by symmetry breaking. To do so, we need to consider an appropriate interaction between the dark sectors which is not linear in terms of dark matter energy density. In this context, two frameworks are presented, one in which the form of the interaction between dark sectors is borrowed from the scalar-tensor theories but employs two dark energy scalar fields giving rise to a transient acceleration and the other where we try to obtain a permanent acceleration arisen from symmetry breaking by employing appropriate interactions (not derived from an action) between dark sectors of the Universe. In this case the Universe tends to a de Sitter space time with positive acceleration. We also examine the stability of the model and illustrate our results via numerical depictions. Our motivation to propose this model, as stated before, is that in a symmetry breaking procedure where the scalar field rolls down its potential, as we will show, the potential reduction not only is not in favor of acceleration but also is against it.

In our study, by "symmetry breaking," we generally mean the procedure where the potential gets the shape of a "symmetry breaking potential" even though the field has not yet been settled at the new minimum.

We use the units $\hbar = c = 1$.

2. Role of positive potential in driving the acceleration

In a spatially flat Friedmann Robertson Walker space-time, filled (nearly) with dark matter ρ and dark energy scalar fields ϕ_i with potentials $V(\phi_i)$, the Friedmann equations are

$$H^2 = \frac{1}{3M_P^2}\left(\frac{1}{2}\sum_i \dot{\phi_i}^2 + V(\phi_i) + \rho\right), \tag{1}$$

$$\dot{H} = -\frac{1}{2M_P^2}\left(\sum_i \dot{\phi}^2 + \rho\right), \tag{2}$$

where in terms of the scale factor $a(t)$, the Hubble parameter is given by $H = \frac{\dot{a}(t)}{a(t)}$. A dot indicates time derivative and $M_P = 2.4 \times 10^{18}$ GeV is the reduced Planck mass. The positive acceleration of the Universe is specified by $\ddot{a} > 0$ which, by using $\dot{H} + H^2 = \frac{\ddot{a}}{a^2}$, leads to

$$\dot{H} + H^2 = \frac{1}{6M_P^2}\left(-2\sum_i \dot{\phi_i}^2 + 2V(\phi_i) - \rho\right) > 0. \tag{3}$$

This can be rewritten in terms of the deceleration parameter q as

$$q = -\frac{\dot{H} + H^2}{H^2} = \frac{1}{2}(1 + 3\omega) < 0, \tag{4}$$

where ω is the equation of state parameter of the Universe. From (3), it is clear that to have a positive acceleration we need a positive potential which drives acceleration

$$V(\phi_i) > \sum_i \dot{\phi_i}^2 + \frac{\rho}{2}. \tag{5}$$

In models trying to describe onset of acceleration via symmetry breaking, the scalar field is initially settled down at a fixed point, $\dot{\phi} = 0$, then after the symmetry breaking it rolls down its potential. Therefore in these models, after the symmetry breaking, the potential decreases while the kinetic energy increases and these make $\dot{H} + H^2$ more negative and so are not in favor of acceleration as can be seen from (3). In the following section we review two of these models and afterwards we will propose a model which can associate the acceleration to symmetry breaking in a concrete way.

3. A brief review and critical analysis of models ascribing acceleration to symmetry breaking

In this part we study the possible relation between the symmetry breaking and the positive acceleration of the Universe in two well known scalar field models.

3.1. Hybrid quintessence

Based on the "hybrid inflation" model introduced in [7], the Authors of [8] suggested a hybrid quintessence model to study the present acceleration of the Universe. In this model an additional scalar field ψ is employed to trigger the slow roll of the quintessence field ϕ via symmetry breaking at late times. The potential is taken as

$$V(\phi, \psi) = \beta\phi^4 + \alpha\phi^2 + h\psi^2\phi^2 + \lambda\psi^4 + \mu\psi^2, \tag{6}$$

where α, β, h, λ and μ are real constants satisfying $\{\beta > 0, \lambda > 0, \mu < 0, \alpha > 0, h < 0\}$ and $\{h^2 - 4\lambda\beta < 0, h\mu - 2\alpha\lambda > 0, h\alpha - 2\beta\mu > 0\}$ [8]. When $\psi^2 < \psi_c^2$, where $\psi_c^2 = -\frac{\alpha}{h}$, the effective mass squared of ϕ is positive and this field is settled down to $\phi = 0$. But when ψ becomes greater than the critical value, $\psi^2 > \psi_c^2$, the squared effective mass of ϕ becomes negative. $\phi = 0$ as the local maximum of the potential becomes an unstable state, hence ϕ rolls down the potential, leading to the present acceleration of the Universe as claimed in the scenario described in [8]. Finally these fields settle down to the minimum of the potential and acquire