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ABSTRACT

Equations of motion of an interface between two phases with arbitrary equations of state are obtained. It is found that there may take place a process of metastable vacuum burning. It is shown that under some conditions the process of the new phase bubble expansion is described by the detonation wave equations. Possible cosmological consequences of the metastable phase burning effect are briefly discussed.

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In our recent papers [1)-3)] we have started the systematic study of an interface between two phases arising in phase transitions changing a symmetry group of elementary particle interactions. The method developed by Israel [4)] of investigating thin-wall shells in general relativity was used. In Ref.1 the pure vacuum case was studied and in Ref.2 constraints on parameters of a decaying metastable state of the Universe were obtained.

In the present paper we shall investigate the boundary of phase separation with arbitrary equations of state of the phases but for the sake of simplicity we shall consider only the limiting case when one can neglect effects of gravitation. In particular, we shall show that there may take place an interesting effect of vacuum burning which in turn could result in changing of a commonly believed picture of the early Universe phase transitions and in particular in a possible changing of the popular inflationary scenarios [5),6)].

Let us consider a spherically symmetric boundary of phase separation (i.e. a shell). Let p_{out}, ε_{out} be a pressure and an energy density measured by an observer in a frame system comoving with the outer phase while p_{in}, ε_{in} are the characteristics of the inner medium. Let S_i^j be the tensor of a surface energy-momentum density on the shell. In the spherically symmetrical case under consideration the only non-vanishing components are S_0^0, S_2^2 and S_3^3, the last two of them being equal.

Let $\rho(\tau)$ be the radius of the new phase bubble and τ be the time measured by the observer with respect to which the boundary of phase separation is being at rest. We obtained from the energy-momentum conservation law $T_{\mu\nu,\nu} = 0$ the following equations of motion of the boundary of phase separation:

$$\frac{dS_0^0}{d\tau} + \frac{2\dot\rho}{\rho}\left(S_0^0 - S_2^2\right) = (\varepsilon+p)_{out}\,\dot\rho\sqrt{1+\dot\rho^2} - $$
$$-(\varepsilon+p)_{in}\left[\dot\rho\sqrt{1+\dot\rho^2}\left(v^{0\,2}+v^{1\,2}\right) - v^0 v^1\left(2\dot\rho^2+1\right)\right], \qquad (1a)$$

$$\frac{S_0^0\ddot\rho}{\sqrt{1+\dot\rho^2}} + \frac{2S_2^2\sqrt{1+\dot\rho^2}}{\rho} = \varepsilon_{out} - \varepsilon_{in} + (\varepsilon+p)_{in}\left[v^0\sqrt{1+\dot\rho^2} - v^1\dot\rho\right] -$$
$$-(\varepsilon+p)_{out}\left(1+\dot\rho^2\right), \qquad (1b)$$

where $\dot{\rho} \equiv d\rho/d\tau$ and v^i are components of a 4-velocity of the inner medium with respect to the centre of a bubble. We have taken that the centre of the bubble is at rest with respect to the outer medium. Being rewritten in terms of medium velocities relative to the shell these equations become

$$\frac{dS_0^{\,0}}{d\tau} + \frac{2\dot{\rho}}{\rho}\left(S_0^{\,0} - S_2^{\,2}\right) = (\varepsilon + p)_{out}\, \frac{r'}{1 - r'^2} - (\varepsilon + p)_{in}\, \frac{u}{1 - u^2} \,, \tag{2a}$$

$$\frac{S_0^{\,0}\ddot{\rho}}{\sqrt{1+\dot{\rho}^2}} + \frac{2 S_2^{\,2}\sqrt{1+\dot{\rho}^2}}{\rho} = p_{in} - p_{out} + (\varepsilon + p)_{in}\, \frac{u^2}{1-u^2} - (\varepsilon + p)_{out}\, \frac{r'^2}{1 - r'^2} \,, \tag{2b}$$

where u is the 3-velocity of the inner medium and $r' \equiv dr/dt = \dot{\rho}/\sqrt{1 + \dot{\rho}^2}$ is the shell velocity in co-ordinates of the observer which is resting with respect to the centre of the bubble. In the derivation of Eqs.(1a), (1b) and (2a), (2b) we have assumed also that both the inner and the outer medium are ideal and all the entropy production is connected with the transient layer and could be attributed to the shell.

We would like to mention that we have obtained also equations similar to Eqs.(1) and (2) with the full accounting for general relativity effects using Israel matching conditions for two arbitrary spherically symmetric metrics. These matching conditions take on the form of Eqs.(1) and (2) in the limit of the flat space-time and if one may neglect the back reaction of a matter on the geometry. Therefore, in the framework of Eqs.(1) and (2) we may investigate the decay of the phase with the pure vacuum equation of state $(\varepsilon + p) = 0$ too in the limit when effects of gravitation are vanishing, (i.e. if the bubble size is much less than the horizon and $|\Delta T_i^{\,j}| \ll (S_i^{\,j})^2/M_{p\ell}^2$).

The equations obtained are the most general ones and are appropriate for investigating motion of any shell including as particular cases the motion of detonation waves, of condensation discontinuities, etc.

One can see from Eqs.(1a) and (1b) that two different phases with pure vacuum equations of state $(\varepsilon + p)_{in} = (\varepsilon + p)_{out} = 0$ could be matched only at the singular shell $S_i^{\,j} \neq 0$. Using the explicit form of energy-momentum tensor of a scalar field one may obtain that in the pure vacuum case $S_i^{\,j} = S\,\delta_i^{\,j}$. Then it follows from Eqs.(1) that

$$S = const \,, \tag{3a}$$

$$\dot{\rho}^2 = \left(\frac{\varepsilon_{out} - \varepsilon_{in}}{3S}\right)^2 \rho^2 - 1 \,. \tag{3b}$$

The solution of this equation in co-ordinates of the observer resting at the centre of the bubble takes on the form

$$r^2 - t^2 = \left(\frac{3S}{\varepsilon_{out} - \varepsilon_{in}}\right)^2 \,, \tag{4}$$

that is the well-known [7] equation of motion of a pure vacuum shell.

The most interesting are however just non-vacuum shells. Indeed, an expansion of an even initially pure vacuum shell is furnished with a particle production.

In this connection the crucial question arises: does such a bubble remain empty? Recently there was published a number of papers [8] devoted to the investigation of particle production by the vacuum shell.

This process is usually considered as a small perturbation of a vacuum solution (4). However the full investigation of the problem should include the solution of Eqs.(1). A structure of the tensor $S_i^{\,j}$ should be taken then from a quantum field theory.

In the present paper we shall restrict ourselves to the consideration of some peculiar properties of the system (1) which are not affected essentially by the detailed structure of $S_i^{\,j}$.

Let us consider first of all the case when the outer medium is a pure vacuum with $\varepsilon > 0$. As far as the inner medium is concerned we shall suppose that its vacuum energy density equals zero and that its state is not a vacuum one. In this case Eqs.(1) allow the existence of a shell with $S_0^{\,0} = 0$. We however by no means may take $S_2^2 = 0$. Indeed, our shell is the source of particles and this necessarily brings in its train non-equality to zero on $S_2^{\,2}$ component of the shell stress tensor. We may assume further that the inner medium is in thermal equilibrium (in this case we consider the whole transient non-equilibrium layer as a thin one and attribute it to the shell). For simplicity, let the chemical potential of the inner medium equal zero, then $(\varepsilon + p)_{in} = Ts$. The inner medium possesses the non-zero entropy density s while the outer medium entropy density equals zero. Consequently the shell has a non-vanishing entropy source

$$\sigma = \frac{s u}{\sqrt{1-u^2}} \quad . \tag{5}$$

It follows from Eq.(2a) that

$$\tilde{S}_2^{\,2} = \frac{\rho T}{2\dot{\rho}\sqrt{1-u^2}}\, \sigma \quad , \tag{6}$$

(we shall denote by $\tilde{S}_2^{\,2}$ the part of $S_2^{\,2}$ component of the shell stress tensor responsible for the entropy production).

If the inner medium is at rest with respect to the centre of the bubble ($v^1 = 0$, $v^0 = 1$) then it follows necessarily from Eqs.(1) that $\epsilon_{in} = \epsilon_{out}$. We consider this case especially because it is a limiting case of a homogeneous isotropic Friedman-Robertson-Walker world at $M_{p\ell} \to \infty$. Using formulas given in Ref.2 one can obtain that even taking into account general relativity effects one can match two homogeneous isotropic worlds on the shell with $S_0^{\,0} = 0$ only if $\epsilon_{in}(t_{in}) = \epsilon_{out}(t_{out})$.

Now let the inner medium be moving, $v^1 \neq 0$. In this case we obtain in the limit $\dot{\rho} \to \infty$ (i.e. in the limit of the shell moving with the velocity of light)

$$\varepsilon_{in} - p_{in} \cdot v = \varepsilon_{out}(1+v) \quad , \tag{7}$$

where v is the velocity of the medium, $v \equiv v^1/v^0$. In terms of medium velocity u with respect to the shell we obtain in the limit $\dot{\rho} \to \infty$

$$\varepsilon_{in} u - p_{in} = \varepsilon_{out}(1+u) \quad . \tag{8}$$

We have written here both formulas (7) and (8) since in the limit $\dot{\rho} \to \infty$ they describe two different situations leading to the same result only in the limit $u \to 1$, $v \to 1$.

It follows from Eqs.(7) and (8) that independently of the smallness of $\tilde{S}_2^{\,2}$ all the metastable vacuum energy is processed into the inner medium energy.

It is obviously the direct consequence of $S_0^{\,0} = 0$ that the energy release in the phase transition cannot be attributed to the wall kinetic energy. On the magnitude of $\tilde{S}_2^{\,2}$ there depends the rate of processing of the vacuum energy into the inner medium one. The case $S_0^{\,0} = 0$, $S_2^{\,2} \neq 0$ is nevertheless quite acceptable physically. In fact one deals with it for example every time one observes the combustion process. Therefore we may say that we are dealing here with the process of vacuum combustion. The quantity $S_0^{\,0}$ is in fact the amount of energy contained inside the transient layer between two phases under investigation. We know that for a chemical combustion process the $S_0^{\,0} = 0$ approximation is a good one (formally speaking $S_0^{\,0}$ equals zero if in the limit of an infinitely thin transient layer $T_0^{\,0}$ has only finite discontinuity and does not possess any δ-functional singularity) while in the vacuum burning process it may prove not to be the case.

Let us now proceed to the consideration of bubbles with $S_0^{\,0} \neq 0$. We shall show that the effect of vacuum combustion may take place in this case too.

Particles created during the phase transition can form bound states with the wall [9] so that $S_0^{\,0} = S_0^{\,0}(\tau)$ and $S_0^{\,0}$ is growing together with the rise of ρ . We shall neglect this effect and shall take that $S_0^{\,0} = \text{const.}$ The particle production results in $S_2^{\,2} = S_0^{\,0} + \tilde{S}_2^{\,2}$, where the quantity $\tilde{S}_2^{\,2}$ is connected with the entropy source (6). Generally speaking $\tilde{S}_2^{\,2}$ is a complicated function of the state of a medium and of the shell motion. For example, $\tilde{S}_2^{\,2}$ could contain terms proportional to ρ, $\dot{\rho}$, $\ddot{\rho}$, etc. However in all these cases the magnitude of $\tilde{S}_2^{\,2}$ is only increasing and therefore the amount of vacuum energy transformed into the energy of the inner medium is also growing. Since we are interested here in the question a new phase bubble is empty or not we shall investigate the bubble motion taking $\tilde{S}_2^{\,2} = \text{const.}$ and thus shall obtain a lower bound on the heat production from the vacuum during the vacuum bubble expansion. One can integrate Eq.(2b) assuming that u, ε_{in}, p_{in} and $\tilde{S}_2^{\,2}$ are constant:

$$\frac{\sqrt{1+\dot{\rho}^2}}{\rho} = \frac{\varepsilon_{out} - \varepsilon_{in} + (\varepsilon+p)_{in}/(1-u^2)}{3S_0^{\,0} + 2\tilde{S}_2^{\,2}} + C\rho^{-\frac{3S_0^{\,0}+2\tilde{S}_2^{\,2}}{S_0^{\,0}}} \quad , \tag{9}$$

C being the integration constant. For the pure vacuum outer medium Eq.(9) with $C \neq 0$ coincides with the equation of motion of a bubble possessing a non-zero Schwarzschild mass [1]. Therefore initial conditions for a spontaneously nucleated bubble require $C = 0$ *). In any case at large enough ρ the specific value of C becomes unessential. From Eqs.(9) and (2a) at $\rho \to \infty$ we then obtain

$$2\tilde{S}_2^2\left(\varepsilon_{out} + p_{in} - u^2(\varepsilon_{out} - \varepsilon_{in})\right) = \left(3S_0^0 + 2S_2^2\right)u(\varepsilon+p)_{in} . \quad (10)$$

We see from Eq.(10) that $\varepsilon_{in} \sim \varepsilon_{out}$ at any arbitrarily small value of $\tilde{S}_2^2$ provided $u \sim \tilde{S}_2^2/S_0^0$. We would note however that the magnitude of ε_{in} may not serve as an adequate criterion in the question of whether the vacuum is burning or not. To find such a criterion let us proceed as follows. Denote by E_{part} the part of energy release absorbed by the inner medium while E_{kin} is the kinetic energy of the wall $E_{kin} = 4\pi\rho^2 S_0^0\sqrt{1+\dot{\rho}^2}$. Clearly

$$E_{part}/E_{kin} = \frac{4}{3}\pi\rho^3\varepsilon_{out}/E_{kin} - 1 . \quad (11)$$

We shall say that a vacuum is burning if $E_{part}/E_{kin} \gtrsim 1$. From Eqs.(11) and (9) we find

$$E_{part}/E_{kin} = \frac{2\varepsilon_{out}\tilde{S}_2^2(u-1) + 3uS_0^0\varepsilon_{in}}{3S_0^0 u(\varepsilon_{out} - \varepsilon_{in})} . \quad (12)$$

Using the relation between ε_{in} and u following from Eq.(10) at the condition that the inner medium has the equation of state $p_{in} = v_S^2\varepsilon_{in}$, v_S being the sound velocity, we finally obtain

$$E_{part}/E_{kin} = \frac{2\tilde{S}_2^2}{3S_0^0} \cdot \frac{(1-u)(u-v_S^2)}{u(1+v_S^2)} . \quad (13)$$

We see that E_{part}/E_{kin} vanishes at $u = 1$ or $u = v_S^2$ and takes its maximum at $u = v_S$. Thus, at $S_0^0 = \text{const.}$ and $\tilde{S}_2^2 = \text{const.}$ we obtain $E_{part}/E_{kin} \gtrsim \tilde{S}_2^2/S_0^0$. What could be the value of this ratio?

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*) The critical radius of a bubble nucleated in a thermostat (where a bubble may be nucleated with a non-vanishing mass) is determined by the conditions of equilibrium of a bubble in a medium $\dot{\rho} = 0$, $\ddot{\rho} = 0$. In this case one obtains from Eq.(1b) that $\rho_0 = 2S_2^2/(p_{in}-p_{out})$, that is, the well-known formula of thermodynamics.

It seems to us rather plausible that it could be of order of 1. First of all it seems that S_0^0 is determined by the value of a scalar coupling constant λ while the $\tilde{S}_2^2$ is determined by the value of a maximal coupling constant of a model (gauge coupling g in GUT's). The most interesting are models with a supercooling which take place just in GUT's with $\lambda \sim g^4$ (see, e.g. Ref.10). In addition, in GUT phase transitions with supercooling the transitions take place at temperatures of order of inverse confinement radius and all the couplings increase.

Now let the outer medium not be pure vacuum $(\varepsilon + p)_{out} = (Ts)_{out}$. In this case the number of possible regimes even increases:

1) It is possible that $\dot{\rho} \to \infty$ when $\rho \to \infty$. Then $v = \text{const.}$ moreover

$$v = \frac{(\varepsilon+p)_{in} - (\varepsilon+p)_{out}}{(\varepsilon+p)_{in} + (\varepsilon+p)_{out}} . \quad (14)$$

2) The shell motion with the constant velocity $\dot{\rho} \to \text{const.}$ at $\rho \to \infty$ is possible. At large enough ρ such a shell takes the regime of a detonation wave whose behaviour is well known (see, e.g. Ref.11). (Note that for a plane wall the left-hand sides of Eqs.(2a) and (2b) are identically equal to zero and one obtains the equations coinciding with the corresponding equations of detonation waves (Ref.11).)

Recently in Ref.12 it has been supposed that the bubble rise in phase transitions in the early Universe is similar to the process of the spherical detonation wave motion. Here we have seen that the shell may indeed expand as a detonation wave and have learned at what conditions this takes place. This regime may exist in the vacuum dominated case too. *) At small values of $(Ts)_{out}$ the shell velocity tends to the constant value close to the velocity of light (but not equal to !) and the inner medium characteristics u, ε_{in}, p_{in} obey Eq.(8). This regime is rather remarkable because in this case there takes place the total processing of vacuum energy into the medium energy independently of the magnitudes of S_0^0 and $\tilde{S}_2^2$ (because of constancy of $\dot{\rho}$ the energy released cannot lead to the increase of a shell kinetic energy at large ρ).

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*) Without accounting for gravitation, we think that gravitational effects will be essential here because of an exponential decrease in a particle number density in the outer region. It may not be excluded, however, that the effective outer temperature the expanding shell "feels" cannot be less than the Hawking temperature of the de Sitter world. An article on the general relativity effects on the shell motion is now in preparation and will be published elsewhere.

Here we have investigated only a few asymptotical regimes of bubble expansion. To trace the bubble motion starting from given initial data we need to know S_i^j as a function of ρ, $\dot{\rho}$, etc. At the moment we know nothing on the stability of various regimes.

We may however suppose that the bubble expansion is similar to the combustion phenomenon and may expect at least that if initial temperature inside a bubble is high enough then this temperature value will be maintained during the expansion.

In the inflationary scenario [5] the main problem is that the expanding bubble has been supposed to be empty and thus the subsequent collisions lead to unacceptably large inhomogeneities [13]. But in the case of vacuum burning the whole energy release (or its considerable part) is converted directly into the energy of the inner medium and it is possible that the problem of too large inhomogeneities will not arise. Thus in the scenario with the vacuum burning the same cosmological problems seem to be possibly solved as in the inflationary scenario [5] not supposing however that the visible part of the Universe is inside one bubble as in Ref.6. The phenomenon of inflation of a space region occupied by a fluctuation along with the subsequent heating of the interiors may prove to be useful in the proposed scenario too, but contrary to the new inflationary scenario [6] we do not need such fine tuning of parameters.

Furthermore, in connection with Λ-term problem we would prefer not to attribute the non-zero vacuum energy density to the metastable phase with unbroken symmetry (effective potential for scalar field must be convex therefore if at zero temperature effective potential is defined everywhere then in the case of spontaneously broken symmetry there is a plateau in this potential and the - problem of induced Λ - term may merely be an artefact of perturbation theory approach [14]). It is sufficient for us to assume only the very existence of a supercooled state of the early Universe.

In GUT phase transitions it is in fact impossible to arrange super-cooling below some temperature which is of the order of the inverse radius of confinement for corresponding phase [16]. We however may suppose the existence of a sequence of phase transitions instead of a single one [15],[10]. Then the total entropy in the Universe (neglecting for a moment a possible contribution due to inflation [6]) is equal [16] to

$$\Sigma = \prod_i \left(T_i^*/T_{ic}\right)^3 s_0 \quad ,$$

where s_0 is an initial entropy, T_{ic} the temperature of i^{th} phase transition, T_i^* is the temperature after reheating. If the temperature after the last phase transition which provides considerable entropy increase is of order M_X the subsequent generation of baryon asymmetry of the Universe may follow the standard scenario [17]. Note by the way that the burning of metastable state is highly non-equilibrium process so baryon asymmetry may be generated directly through the combustion and it seems not to be a necessary requirement in this case to have a temperature of order M_X after reheating.

As it was seen there are possible regimes of a bubble expansion in which the inner energy density remains constant during expansion. The velocities of a medium with respect to bubble center are usually large. Therefore when all the bubbles have collided and the phase transition has been completed there may be prepared a state with a nearly uniform energy density distribution but with randomly distributed (collective) velocities of medium elements. Such an initial state could lead to the formation of caustics and to the subsequent formation of large scale structures in the Universe [18].

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