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Particle production in a two-brane collision and Reheating of the Brane Universe

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Abstract. We study particle production at the collision of two domain walls in 5-D Minkowski spacetime. This may provide the reheating mechanism of an ekpyrotic brane universe [1]. We evaluate a production rate of particles confined to the domain wall. The reheating temperature is evaluated as $T_R \approx 0.88 \bar{g}^{1/4}$. In order to have the baryogenesis at the electro-weak energy scale, the fundamental mass scale is constrained as $m_\eta \sim 1.1 \times 10^7$ GeV for $\bar{g} \sim 10^{-5}$.

We study how we can recover the hot big bang universe after the collision of the branes. Here we investigate quantum creation of particles, which are confined to the brane, at the collision of two branes [2]. It may be difficult to deal properly with the collision of two branes in basic string theory. So we adopt a domain wall constructed by some scalar field as a brane, and analyze the collision of two domain walls in a 5-D bulk spacetime. In order to analyze particle creation at the brane collision, we consider the simplest situation, that is the collision of two domain walls in 5-D Minkowski. To construct a domain wall structure, we adopt a real scalar field $\Phi$ with a double-well potential. The equation of motion for $\Phi$ has a static kink solution called a domain wall, which is described by $\Phi(y) = \tanh(y/d)$, where $d$ is the thickness of the wall.

When a domain wall moves with constant speed $v$ in the $y$ direction, we obtain corresponding solution by boosting that static solution as $\Phi_v(y, t)$. In order to discuss the collision of two domain walls, we first have to set up the initial data. Provide a kink solution at $y = -y_0$ and an antikink solution at $y = y_0$, which are separated by a large distance and approaching each other with the same speed $v$. We solve the dynamical equation numerically.

The collision of two walls has been discussed in 4-D Minkowski space [3]. Although we discuss the domain wall collision in 5-D Minkowski space, our basic equations are exactly the same as the cited case, and we find the same results as there.

Let us show the numerical results for typical initial velocities, $v = 0.4, 0.2$. Here we show the latter case. The evolution of $\Phi$ is depicted in Fig. 1, while that of the energy density is shown in Fig. 2. From Figs. 2, we find some peaks in the energy density, by which we define the positions of moving walls ($y = \pm y_W(t)$). Where the initial velocity $v = 0.2$, the collision occurs twice, while where $v = 0.4$, the collision occurs once. In particular, the results are very sensitive to the initial velocity $v$.

Once we find the solution of colliding domain walls, we can evaluate the time evolution of a scalar field on the domain wall. Since we assume that we are living on one domain wall, we are interested in production of a particle confined to the domain wall. We assume that there is some coupling between a 5-D scalar field $\Phi$ that is responsible for the domain wall and a particle on
Collision of two domain walls where the initial velocity $\nu = 0.2$. The time evolution of the scalar field $\Phi$ is shown from $t = 0$ to 150. We find that collision occurs twice, at $t \approx 58$ and 77. We set $\lambda = 1.0$.

The time evolution of scalar field energy density in the case of Fig. 1. From this figure, we find clearly that collision occurs twice.

Hence we have to know the value of the scalar field $\Phi$ on the domain wall, i.e. $\Phi_W(\tau) = \Phi(t, y_W(t))$. Since the wall is moving in a 5-D Minkowski space, we have to use the proper time $\tau$ of the wall. Let us consider a particle on the domain wall described by a 4-D scalar field $\psi$. Although the confined scalar field may also be extended in the 5-th direction because the domain wall has a finite width, we assume here that this scalar field is 4-D, which means that it has the value only at the position of the domain wall ($y = y_W(t)$). This ansatz may be justified [2]. Assuming an interaction with the scalar field $\Phi$ as $\propto \bar{g}^2 \Phi_W^2 \psi^2$, where $\bar{g}$ is a coupling constant, we find the dynamical equation for $\psi$ and it is easy to quantize this scalar field $\psi$ because our background spacetime is 4-D Minkowski space. Approaching a usual canonical quantization scheme, as a result, the number density of produced particles is given by $n = \int |\beta_k|^2 d^3 k$, where $\beta$ is the Bogolubov coefficient. Now we estimate the particle production by the domain wall collision numerically.

Summary our result, the energy density of created particles was approximated as $\rho \approx 4\pi \Phi_0 \bar{g}^4 N_b$ where $\Phi_0$ is the maximum amplitude of $\Phi_W$, $N_b$ is the number of bounces at the collision, and $\bar{g}$ is a coupling constant of a particle to the scalar field of a domain wall. If this energy is converted into standard matter fields, we find the reheating temperature as $T_R \approx 0.88 \times \bar{g} \frac{N_b^{1/4}}{\langle g_{\text{eff}}/100 \rangle^{-1/4}}$. We find that the particle creation is affected more greatly by the coupling constant $\bar{g}$ than the other two parameters $\nu$ and $\lambda$. The initial velocity changes the collision process, that is, the number of bounces at the collision, but this is less sensitive to the temperature. The thickness of a domain wall $d$ changes the width of potential $\Phi_W^2(\tau)$ of a particle field $\psi$, and it changes the typical energy scale of created particles, which is estimated as $\omega \sim 1/d$.

References

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