Flavored Baryogenesis

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Understanding the origin of the matter-antimatter asymmetry of the Universe is one of the greatest challenges at the interface of cosmology, particle physics, and nuclear physics. One of the most attractive mechanisms of "baryogenesis" (from the Greek "generation of matter") involves particles whose existence can be probed with laboratory experiments. Conclusive tests of this scenario require, beside experiments, robust theoretical calculations of the non-equilibrium quantum transport of particles in the early Universe, which are currently lacking. We have focused on developing the tools that allow calculations of the matter-antimatter asymmetry in a broad class of models and we have identified a new source for the matter-antimatter asymmetry, originating in the quantum mechanical mixing of particles carrying different "flavor" quantum numbers.

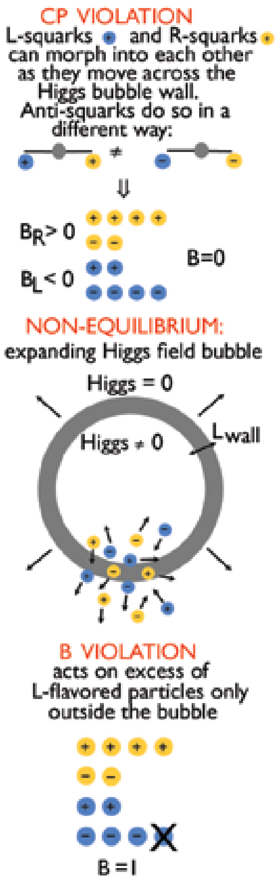

Fig. 1. Stages of "flavored" electroweak baryogenesis: (1) Bubbles of non-zero Higgs field (similar to vapor bubbles in boiling water) form and expand; (2) CP-violating propagation across the bubble generates non-zero L and R baryon densities, with $B_L+B_R=0$; (3) B violation destroys B_L, making net $B\neq 0$; (4) The asymmetry is captured by making net $B\neq 0$. Finally the asymmetry is captured by the expanding bubble that eventually fills the universe.

To a very good approximation, the laws of physics do not distinguish between matter and antimatter. The Universe would look almost exactly the same if every particle were replaced by its antiparticle. Yet the observed Universe is made up of matter and not antimatter. In order to produce the observed asymmetry, there must have been a tiny imbalance of one part in ten billion between matter and antimatter in the primordial hot plasma one microsecond after the big bang. As the Universe evolved and cooled down, most of the antimatter annihilated with matter, leaving behind the small initial excess of matter, which is still enough to make up the observed stars and galaxies. Understanding how the observed imbalance has developed during cosmic evolution is one of the great open questions at the interface of cosmology, particle physics, and nuclear physics.

A number of explicit baryogenesis mechanisms have been proposed. All mechanisms involve three basic ingredients, first identified by Sakharov in 1967 [1]: (1) violation of conservation of baryon number (= "matter" number), which distinguishes protons from antiprotons; (2) violation of CP symmetry (C= charge conjugation, i.e., interchange of particles and antiparticles; P= mirror reflection); and (3) departure from thermal equilibrium.

We have focused on the so-called electroweak baryogenesis scenario [2], in which the matter-antimatter asymmetry develops during the electroweak phase transition, at which the Higgs field acquires a vacuum expectation value that gives mass to all particles that couple to it. This happened when the temperature of the early universe was about 100 GeV (about 100 times the rest energy of the proton), an energy scale accessible in laboratory experiments—directly at high energy colliders and indirectly via precision low-energy measurements, such as the search for the neutron electric dipole moment at the ORNL Spallation Neutron Source, led by nuclear physicists from LANL and ORNL. The fact that we can probe experimentally the relevant degrees of freedom implies that in any given extension of the Standard Model we can test whether electroweak baryogenesis works or not. Currently, the main obstacle to such a test stems from large theoretical uncertainties (several orders of magnitude) arising from uncontrolled approximations in the treatment of particle transport in the early universe. We have provided the framework to perform robust first-principles calculations based on a controlled power-counting [3], thus removing the uncontrolled part of the previous treatments. In addition, as we discuss in greater detail below, for a broad class of models we have identified a new dominant source of matter-antimatter asymmetry [4].

We have developed a new formalism and a new physical picture to describe how CP asymmetries (i.e., differences in particle and antiparticle propagation) arise in electroweak baryogenesis. The key observation is that in most extensions of the Standard Model, particles that carry baryon number come in different flavors, that is, feel different interactions or forces. The simplest example of this is provided by left (L) and right (R) "squarks" in supersymmetric models. We have realized that CP asymmetries can arise through coherent flavor oscillations (i.e., morphing of one flavor into another) of all the species that couple to the Higgs particle at the electroweak phase transition. We have then formulated the appropriate transport equations that describe the physics of flavor oscillations and at the same time take into account collisions of particles in the hot environment of the early universe. We have tested the new ideas and formalism within a simplified model that involves only particles of spin zero (such as squarks), providing both numerical solutions and analytical insight. This has to be considered the first step

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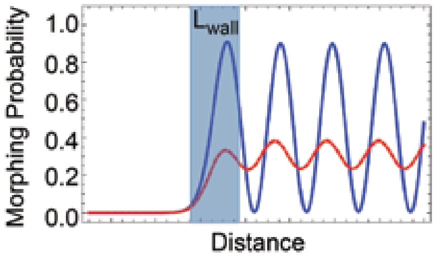

Fig. 2. CP violation at work: As squarks fly across the bubble, the probability for an L-squark to morph into an R-squark (blue line) differs from the probability for an L-antisquark to morph into an R-antisquark (red line).

towards a new understanding of electroweak baryogenesis.

The physics of this mechanism is illustrated in Fig. 1. At the electroweak phase transition bubbles of "broken electroweak phase" (similar to vapor bubbles in boiling water) nucleate and expand. The interesting dynamics happen near the bubble boundaries, where on a characteristic length scale L_{wall} the Higgs field goes from zero to a finite value. As the Higgs field changes, so do the masses and mixing of all particle species that couple to the Higgs, such as L- and R-squarks. If CP symmetry is violated, then L-squarks morph into R-squarks differently than their corresponding antiparticles, as illustrated in Fig. 2. So starting from a CP-conserving equilibrium initial state, a CP asymmetry can arise through coherent oscillations, when the particles cross the boundary between broken and unbroken electroweak phase. In the unbroken phase, there are additional high-temperature processes that then convert this CP asymmetry into the baryon asymmetry that becomes the visible matter in the Universe today.

Within this simple model, we have shown how to derive from first principles, using non-equilibrium field theory, the quantum mechanical Boltzmann equations that describe the dynamics of CP-violating flavor oscillations and collisions in the early Universe. Our derivation can be generalized to any model because it is based on a new power counting based on the hierarchy of relevant length scales: the de Broglie wavelength of the particles, collision mean free path, and flavor oscillation length.

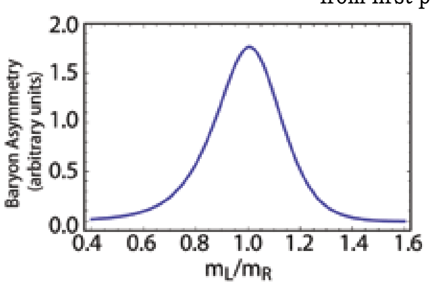

Fig. 3. Matter-antimatter asymmetry versus the ratio of L- to R-squark masses. The Large Hadron Collider might discover supersymmetry and measure mL/mR .

Using numerical methods, we have solved the transport equations exactly without ansatz for the functional form of the density matrices (as far as we know this is the first full solution of quantum kinetic equations in a spatially non-homogeneous system). We have demonstrated the existence of a resonant enhancement in matter production when the flavor oscillation length is comparable to the thickness of the bubble wall. The resonance is determined by the relative value of the mass parameters of the mixing particles in the underlying theory (see Fig. 3). We have determined how the width of the resonance depends on the parameters of the underlying theory, and have shown that the resonant enhancement is relevant in significant regions of the supersymmetric parameter space.

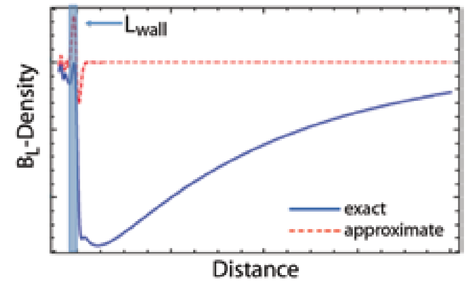

Fig. 4. Exact and approximate L-squark density profiles versus distance from the bubble wall.

We have also investigated the impact of collisions in various regimes that correspond to different mixing particles in realistic extensions of the Standard Model. As expected, larger couplings (more frequent collisions) reduce the generated asymmetry near the bubble and lead to shorter density tails in front of the bubble wall, thus suppressing the final matter-antimatter asymmetry.

Finally, we have compared our results with the existing "state-of-the-art" treatments of this problem by Konstandin, Prokopec, Schmidt, and Seco (KPSS) [5]. Comparison of our exact solution with the KPSS approximation scheme reveals dramatic failures of the latter, as illustrated in Fig. 4. We conclude that: (1) the power counting of KPSS breaks down in the important resonant regime and misses the generation of diffusion tails, and (2) this leads to substantial underestimation of the final matter-antimatter asymmetry by KPSS.

In summary, we have identified a new source of matter-antimatter asymmetry and set up the foundations for robust quantum transport computations relevant for a large class of electroweak baryogenesis models.

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[5] Konstandin, T. et al., *Nucl Phys B* **738**, 1; hep-ph/0505103 (2006).