ELECTROWEAK BARYOGENESIS

DAVID B. KAPLAN
Institute for Nuclear Theory NK-12, University of Washington
Seattle, WA 98195, USA

ABSTRACT

Baryogenesis during the electroweak phase transition is a plausible scenario for
the origin of matter in the Universe. Furthermore, it has the advantage over
other scenarios in that one can imagine the much of the physics involved may
be experimentally probed before long. In the past year a consensus has developed
about the major mechanisms involved. In this talk I give an overview of the standard
picture, and discuss briefly the advances over the past year that suggest electroweak
baryogenesis is a robust phenomenon.

1. General Mechanism for Electroweak Baryogenesis

1.1. Why Electroweak Baryogenesis is Interesting

The quantity we wish to explain is $n_B/s$ — the ratio of the baryon density
of the Universe to the entropy — observed to be equal to\(^1\)

$$n_B/s \simeq (0.8 \pm 0.2) \times 10^{-10}$$

(1)

Approximately thirty years ago Sakharov outlined three basic requirements for an
explanation of this ratio from microphysics. These are (1) B violation; (2) C and
CP violation; (3) Departure from thermal equilibrium. It is intriguing that all three
ingredients are present in the Standard Model (SM) plus Big Bang: B violation can
occur in the SM, as shown by 't Hooft, and both C and CP violation have been
observed. Departure from thermal equilibrium can occur due to the expansion of
the Universe in the Big Bang theory: it is generic at very early times when the
cooling rate of the Universe is more rapid than particle interactions, but can also
occur at late times if there is a first order phase transition with supercooling\(^2\).

The first models for baryogenesis satisfied the Sakharov criteria in Grand
Unified (GUT) theories, exploiting the fact that the GUT scale was not far from
the Planck scale. Thus baryon violation could exist without being in conflict with
the proton lifetime, and departure from equilibrium could easily result due to the
rapid expansion of the Universe during the GUT epoch. All such theories had
to involve new sources of CP violation, as Kobayashi-Maskawa CP violation alone
proved to be too small to explain the observed baryon asymmetry.

Two subsequently discovered effects threaten the viability of GUT-scale
baryogenesis. The first is inflation, which serves to wash out GUT scale monopoles,
but also washes out any baryon asymmetry produced prior to inflation. For GUT
scale baryogenesis to occur after inflation requires a high reheat temperature, which
requires a strongly coupled inflaton, which in turn tends to give large density perturbations inconsistent with structure formation. A second problem is that it is now thought that the anomalous baryon violation of the SM discovered by ’t Hooft occurs relatively rapidly at high temperature\(^2,3\). These interactions cause any baryon asymmetry to equilibrate to a number proportional to B-L, a quantum number preserved by the SM. “New and improved” GUT scale baryogenesis models must now possess an effective B-L symmetry that is violated at high energies, and the baryogenesis must typically involve a scalar field that can “store up” B-L during inflation, only releasing it after inflation is over. Such a field can be the inflaton itself, or something like a squark or slepton field in supersymmetry (SUSY) models\(^4\). Unfortunately, the only new observable experimental consequences from such elaborate constructs are B or L violation, and even then the rates are very model dependent and can be adjusted to be out of reach. The additional CP violation cannot be observed directly. In fact, due to inflation, one can account for a baryon asymmetry within our horizon while having no net baryon number for the Universe as a whole, thus eliminating the need for CP violation.

It is remarkable that the SM itself gives rise to baryogenesis, even though it predicts at best \(n_B/s \simeq 10^{-20}\), and perhaps a lot less, depending on the Higgs mass. Thus while our very existence can be claimed to be the most compelling evidence for new physics beyond the SM (perhaps only second to the existence of gravity!) it is possible that only relatively minor extensions of the SM at the electroweak scale are required. One bottleneck for electroweak baryogenesis (EWB) proves to be inadequate CP violation from the Kobayashi-Maskawa mechanism (as was found in the original GUT baryogenesis models). Another is the need for departure from thermal equilibrium, which can only occur at the electroweak epoch only if there is a sufficiently strong first order phase transition. As discussed below, this requires a light SM Higgs, or an extension of the Higgs sector.

If baryogenesis proceeds at the electroweak scale, we might hope to see new CP violating effects in terrestrial experiments, such as measurements of the electron and neutron electric dipole moments, or direct detection of the new particles and interactions responsible for additional CP violation. Furthermore, EWB requires there to be a first order phase transition, which places constraints on the Higgs sector which might testable some day. A final argument for considering electroweak baryogenesis is one of economy: any theory of baryogenesis needs to posit physics beyond the SM, but for EWB the additions required are quite minimal.

1.2. The One Basic Mechanism with Four Constraints

The standard picture of electroweak baryogenesis assumes that \(SU(2) \times U(1)\) breaks via a first order phase transition, leading to bubble nucleation and a separation of phases\(^2\). In the symmetric phase, anomalous baryon violation is occurring rapidly, at a rate/unit volume estimated as \(\Gamma_{\text{sym.}} \sim (\alpha_w T)^4\); while in the broken phase the process occurs due to sphalerons and the rate is estimated to be \(\Gamma_{\text{brok.}} \sim M_W^3/(\alpha_w T)^3 \exp[-E_{\text{sp}}/T]\), where \(E_{\text{sp}} \simeq 2M_w/\alpha_w\) is the sphaleron energy\(^3\). In order to produce a baryon asymmetry, it is necessary that as the bubble of broken
phase nucleates and expands, particle interactions with the bubble wall somehow produce a baryon excess in the symmetric phase, where B violation is rapid. However, this baryon asymmetry will be subsequently destroyed, unless the B violation rate in the broken phase be extremely small. That is, the phase transition must be sufficiently strong so that sphalerons are heavy and play no role in baryogenesis.

But how does the baryon asymmetry actually come about? Ref. 6 was the first model proposed for EWB, and it outlined the four basic requirements that have been generally incorporated into other models:

i. Particle interactions with the bubble wall lead to a pile-up of particles in front of the advancing bubble wall. This is how the departure from thermal equilibrium translates into a distortion of the particle distribution functions, and it requires some particles with strong coupling to the Higgs field in the bubble wall.

ii. These particles being swept in front of the bubble carry net SU(2) left-handed doublet number, which biases anomalous baryon violation in the direction of reducing this excess. This requires sufficient CP violation, since doublet number is CP-odd.

iii. Each anomalous event that reduces the doublet number also produces three units of baryon number. Once baryon number is produced in the symmetric phase, it is overtaken by the bubble wall and enters the broken phase, where B violation is effectively absent. This requires a sufficiently strong first order phase transition, as mentioned above, which in turn places constraints on the Higgs sector.

iv. The baryon violation rate is proportional to $\alpha_s^4 \sim 10^{-6}$; given enough time to equilibrate, this rate would drop out of the final value for the baryon asymmetry, but otherwise the resultant baryon asymmetry will be reduced by this factor. Furthermore, $n_B/s \propto 1/g_\ast \simeq 10^{-2}$, where $g_\ast$ counts degrees of freedom at the critical temperature. Thus there is only room for an additional factor of $10^{-3}$ from the CP violating angle and any inefficiency of the dynamical mechanism. This proves to be too severe a constraint to satisfy unless there is an enhance of the form of a ratio of time scales: the excess SU(2) doublets must spend sufficiently long time in the symmetric phase before being overtaken by the bubble wall. This requires significant transport of doublet number into the symmetric phase. Even then, one finds that CP violation must occur at the $10^{-3}$ level or larger in most models.

The model of Ref. 6 consisted of the SM with the addition of three right-handed neutrinos and a singlet scalar (the “singlet majoron model”). The right-handed neutrinos had large Yukawa couplings, satisfying constraint (i); the neutrino mass matrix contained large CP violating angles, satisfying constraint (ii); with the addition of the singlet majoron field, the weak phase transition can be quite strongly first order for a range of parameters, satisfying (iii); finally, significant charge transport of left-handed doublet number into the symmetric phase occurred in the form of low energy left-handed neutrinos (which interact weakly), satisfying (iv). The
model is testable in that it predicts a mass for the $\nu_\tau$ in the range 5-30 MeV, as well as an extended Higgs sector with an extra complex scalar. The constraint on the $\nu_\tau$ mass comes from a generic feature of EWB models that the new CP violation must be sizable.

I now turn to discussing the current status of meeting our four requirements in general extensions of the standard model. As much of the details are contained the the review Ref. 8, I will simply summarize results, and give particular emphasis to advances of the past year.

2. Current Status of the Four Constraints

2.1. Significant Higgs–Particle interaction.

Heavy particles are required, since only they will interact strongly with the Higgs field in the bubble wall. This constraint is no challenge to meet: either the top quark is the engine that drives EWB; or exotic heavy particles such as right-handed neutrinos, squarks, or higgsinos. In a SUSY model with large $\tan\beta$, even the $b$ quarks and $\tau$ leptons might participate.

2.2. Sufficient CP Violation

Old Common Wisdom: Since we see CP violation in the kaon system, it is of great interest to know whether the same CP violation is what gave rise to matter in the Universe. A rough estimate suggests that since CP violation in the SM would vanish if any two quarks of the same charge had the same mass, the dimensionless measure of CP violation should be proportional to $G_F^6 \Pi_{i>j}(m_{u_i}^2 - m_{u_j}^2)(m_{d_i}^2 - m_{d_j}^2) \simeq 10^{-20}$. An explicit computation of GUT scale baryogenesis in minimal $SU(5)$ confirms such a suppression. If this counting is correct, then clearly additional sources of CP violation are required to explain (1). Possible additional sources of CP violation include extra Higgs doublets; massive neutrinos; and SUSY. As mentioned above, typical CP violating angles have to be $10^{-3}$ or greater, which usually has experimental implications. In the two-Higgs and SUSY models, the EDM of the electron is within two orders of magnitude of present bounds; in the singlet Majoron model, $\nu_\tau$ must be within an order of magnitude of the present bound.

New CW: Recently Shaposhnikov and Farrar challenged the above reasoning, which is admittedly naive. There are other, larger, plausible measures of CP violation. And after all, $\epsilon \gg 10^{-20}$ in the kaon system. Ref. 12 claims that in fact KM CP violation can be large enough to explain the baryon asymmetry; however in the past year there have been two challenges to their work, however, which conclude that the naive estimate is correct and that KM CP violation would lead to a baryon asymmetry too small by perhaps ten orders of magnitude. Personally, I find the later work convincing, and believe that new CP violation must be added to any theory of baryogenesis.
2.3. A Strong First-Order Phase Transition.

Old CW: There has been extensive work on the nature of the electroweak phase transition, and there is general agreement that for the SM with one Higgs doublet, the transition is strongly first order in the limit $M_H \ll M_W$ (e.g., as in the Coleman-Weinberg scenario) while being second order in the $M_H \gg M_W$ limit. Perturbative calculations break down for $M_H \simeq M_W$. The maximum value for the Higgs mass where baryon asymmetry produced during the phase transition is not subsequently destroyed in the broken phase was thought to occur at about $M_H \approx 45$ MeV, which is experimentally excluded. It was also thought that extended Higgs sectors, such as 2-Higgs models and the singlet Majoron model are still viable candidates for a sufficiently strong first order phase transition. A notable exception is the minimal SUSY model, which is only viable should there be a relatively light squark.

New CW: There have been two recent advances in studies of the electroweak phase transition. One is a novel application of the $\epsilon$ expansion\(^\text{14}\), which suggests that (i) the phase transition is more strongly first order than perturbation theory suggests, but that (ii) the baryon violation rate in the broken phase is faster than previously calculated. That is, for a given Higgs mass, $\langle H \rangle$ is larger but $\eta$ is smaller in the broken phase, in comparison with perturbative results. The $\epsilon \to 1$ limit is not sufficiently under control to give a precise Higgs bound, however.

A second advance has been in lattice simulations of the electroweak phase transition\(^\text{15}\). These simulations also tend to suggest that nonperturbative effects are important for physically interesting Higgs masses, and that the phase transition tends to be more strongly first order than found in perturbation theory. For example, one simulation found that for a Higgs mass of 80 GeV, $\langle H \rangle/T_c = 0.68$, as opposed to 0.3 from perturbation theory. Thus the upper bound of 45 MeV on the Higgs mass for EWB is probably too conservative, although I have not seen any definitive result replace it. Perhaps the one doublet model is still barely viable so far as the phase transition constraint goes.

2.4 Transport

Old CW: The issue here is one of time scales, and has been a major point of discussion in the literature over the past year. The anomalous baryon violation rate/unit volume in the symmetric phase is parametrized as $\Gamma = \kappa \alpha^4 T^4$. The parameter $\kappa$ is a fudge factor to parametrize our ignorance; there has been some lattice evidence for it to be $O(1)\(^\text{16}\). For a crude estimate of how much baryon number we can make during the electroweak phase transition, assume that there is a region in front of the wall with an excess $SU(2)$ fermion doublets density $\delta n_d$, and that it extends a length $\ell$ in front of the bubble wall. As the bubble wall sweeps through all of space with a velocity $v_w$, each point in space is in the doublet rich region for a time $\delta t \approx \ell/v_w$. During that time the baryon production rate is given roughly by $\Gamma \delta n_d/T^3$. The resultant value for $n_B/s$ is then given by

$$n_B/s \sim \left(\frac{\kappa \alpha^4 \theta_{CP}}{g_s^2}\right) \left(\ell T_c\right) \left(\frac{\delta n_d}{\theta_{CP} v_w T_c^3}\right),$$

(2)
where the excess doublet density $\delta n_d$ is proportional to CP violating parameter $\theta_{CP}$, and is typically proportional to the wall velocity $v_w$ as well. The above formula assumes $\ell$ is short enough that baryon violation does not have enough time to fully equilibrate — otherwise the B violation rate would drop out of the formula$^\ast$.

Since the first term in Eq. (2) is $O(10^{-10})$ for an angle $\theta_{CP} \sim 10^{-2}$, evidently a sizable value for the parameter $\ell$ is crucial for making enough baryon number. If the bubble wall is thin, then particles bounce off it and can be reflected for a long way into the symmetric phase. The method for computing the flux of weak doublets reflecting from the bubble walls was presented in Refs. 6,17,18 for the both the singlet majoron model and the two Higgs model with a thin bubble wall and top quark reflection. Transport properties were considered in Ref. 17, where a Monte Carlo calculation showed a significant “snowplow” effect: lefthanded top quarks were pushed along in a region ranging from 20 to 100 thermal units in front of the bubble wall (Fig. 1). Such a model was shown to easily accommodate the desired baryon asymmetry (1) with $\theta_{CP} = 10^{-2} - 10^{-3}$.

For broad bubble walls — thicker than the mean free path of particles — the process was supposed to progress quasi-statically within the bubble wall, where the time dependent Higgs field acted like a chemical potential for left handed doublet number. This scenario — dubbed “spontaneous baryogenesis” — appeared to work, but only barely, since the factor $\ell$ in Eq. (2) was effectively the wall width, and there were various suppression factors$^{19}$.

$^\ast$ Eq. 2 is for illustrative purposes only — much more sophisticated analyses have been discussed in the literature.
New CW. While the thin wall scenario remains unchanged, there has been a lot of work done recently for phase transitions with a thick bubble wall. Dine and Thomas pointed out a number of suppression factors in the thick wall scenario\textsuperscript{20}. The basic problem they found was that the CP violating effects gave rise to a doublet density in the region of the wall where the Higgs field was large, while baryon violation only occurred where the Higgs field was small. In the adiabatic approximation, there was no transport and little overlap between the two regions; the baryon asymmetry was estimated to be at best two orders of magnitude too small. A second objection to the adiabatic treatment for thick walls was made by Giudice and Shaposhnikov, who pointed out that QCD anomalous events wanted to turn left handed doublets into right handed ones, which in thermal equilibrium completely eliminated the weak doublet density that was biasing baryon production\textsuperscript{21}. Finally there was a preprint by Joyce, Prokopec and Turok which pointed out that diffusion had not been properly accounted for in the adiabatic case, and that it would further suppress baryon violation\textsuperscript{22}.

In fact it was shown in Ref. 23 that diffusion was important and that rather than being detrimental, it helped alleviate the other problems\textsuperscript{*}. Diffusion allows doublet density produced well within the bubble wall to venture out into the symmetric phase where baryon violation is rapid, eliminating the Dine-Thomas objection. In Ref. 23 diffusion equations were solved in the presence of the bubble wall for the two Higgs model with maximal CP violation; the results for one set of parameters is shown in Fig. 2. Note that doublet densities diffuse over 100 thermal

\textsuperscript{*} Some similar conclusions are reached in Refs. 24.
lengths, so that Fig. 2 looks not unlike Fig. 1 which was computed in the thin wall approximation by Monte Carlo.

Fig. 3 shows how the Dine-Thomas objection is evaded. We plot the baryon asymmetry that results as a function of $z_{co}$, the point in the wall where one assumes that baryon violation is cut off. Dine and Thomas argued that $z_{co} \simeq 2.5^*$. Without diffusion, we find their suppression (dotted line). However, including diffusion makes the final result very insensitive to details of baryon violation within the bubble wall, and we see that a CP violating angle of $10^{-2} - 10^{-3}$ once again provides a sufficient baryon asymmetry for the Universe.

Fig. 3 reveals an additional bonus. The diffusion equations properly account for the finite rates of interactions, and one finds that particles are not in front of the wall long enough for strong sphalerons to completely eliminate the left handed doublet density. Rather, there is a competition between the $SU(2)$ and $SU(3)$ anomalies and the final baryon asymmetry is roughly proportional to the ratio of their rates, which makes the final answer quite insensitive to (unknown) nonperturbative physics. Thus the Giudice Shaposhnikov observation leaves EWB not only viable, but less model dependent.

The analysis of Ref. 23 made a number of approximations that are invalid for various extreme limits of the wall velocity or the wall width. A more detailed analysis is found in Refs. 25, which for a wide range of parameters are in general agreement with the analysis described above. Overall, the new CW for this section

* They actually express the cutoff in terms of a value for $\langle H \rangle$, which translates to $z_{co} \simeq 2.5$ in the model considered.
must be described as quite optimistic for EWB.

3. Conclusions... and What Next?

Until last year, there were two apparently unrelated regimes for EWB – the thin wall (“nonadiabatic”, “charge transport”, or “nonlocal”) regime which seemed to work well, but only applied to certain types of Higgs sectors — and the thick wall (“adiabatic”, “spontaneous baryogenesis”, “local”) regime, which had a pretty theory behind it, but appeared to be on the edge of viability. The picture that has emerged recently is much more unified, as seen in the comparison of Figs. 1,2: all EWB is nonlocal, and charge transport plays a crucial role in giving the relatively slow $SU(2)$ anomaly time to make enough baryon number. It seems clear at this point that EWB has come of age and is a viable theory; the question remains, is it right?

In principle, knowing all of the extra particles and interactions in an extension of the SM will allow us to compute the baryon asymmetry generated at the electroweak phase transition, perhaps to an order of magnitude. Such a wealth of knowledge seems far off, however. So far experimental signals have appeared to be quite model dependent, although having enough CP violation has constrained all models seen to date to have experimental consequences within two orders of magnitude of current measurements – either the EDM of the electron, or the $\nu_\tau$ mass. It would be interesting to see if there are any model-independent phenomenological predictions. It would also be interesting to see SUSY models analyzed in depth for their ability to create baryon number at the weak phase transition.

Needless to say, this talk is far from a complete review of EWB, but rather an admittedly biased view of what I consider the most interesting recent developments.

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