Snowmass 2021 Letter of Interest: The Baryon Asymmetry Of The Universe

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The Standard Model cannot explain the observed baryon asymmetry of the Universe. This observation is a clear sign of new physics beyond the Standard Model. There have been many recent theoretical developments to address this question. Critically, many new physics models that generate the baryon asymmetry have a wide range of repercussions for many areas of theoretical and experimental particle physics. It is essential to include a discussion of the matter–antimatter asymmetry in the Snowmass Theory Frontier studies. The proposed white-paper will focus on recent developments with an emphasis on experimental testability.

There is more matter than antimatter in the universe. This asymmetry, quantified as the ratio of baryon density to photon density, is measured at the time of Big Bang Nucleosynthesis (BBN) and the Cosmic Microwave Background (CMB) to be [1] $(n_b - n_{\bar{b}})/n_\gamma = n_b/n_\gamma = (6.10 \pm 0.4) \times 10^{-10}$. Inflation dictates that such an asymmetry must be dynamically generated after reheating, necessitating a mechanism of *baryogenesis*.

In order to produce a matter–antimatter asymmetry, a model of particle physics must satisfy the so-called Sakharov conditions [2]. These are: (i) Baryon number (B) violation, (ii) C and CP violation and (iii) departure from thermodynamic equilibrium. In the Standard Model (SM), (i) Baryon number is anomalously violated in the weak interactions of the SM. Although the rate of B-violating *sphaleron* processes is exponentially suppressed at zero temperature, $\Gamma \sim \exp(4\pi/\alpha_W) \sim e^{-160}$, sphalerons are very efficient at temperatures at which Electroweak symmetry is restored, $T \gtrsim 130$ GeV [3, 4]. (ii) There is CP violation in the CKM matrix, and possibly in the PMNS matrix [5]. It has been argued that the CKM phase is not sufficient (in fact orders of magnitude short of) for producing the BAU. Within the SM there is no SM process to employ the CP violation in the PMNS matrix to produce the BAU. (iii) There are many ways a process could occur out of thermal equilibrium, such as particle decay at temperatures below its mass, or a first-order phase transition. There is no process in the SM that goes out of thermal equilibrium in the early Universe. These shortcomings of the SM are a clear sign of BSM physics. By the nature of the problem, this observation and the related new physics have strong implications for early Universe cosmology.

I. TRADITIONAL BSM PROPOSALS

BSM models that explain the BAU originate from the Sakharov conditions and the shortcomings of the SM to satisfy them. An incomplete summary of BSM ingredients required to produce the observed BAU is given in Table I. There are numerous BSM models that can be (and have been) built by incorporating any number of these new physics sources. For example, leptogenesis models include explicit L violation via Majorana neutrinos, (new) CP violation in the neutrino-mixing matrix and out-of-equilibrium decays of a heavy neutrino. (leptogenesis models rely on SM sphaleron processes to convert a lepton asymmetry to a baryon asymmetry.) Most Electroweak baryogenesis models use the SM sphaleron processes to violate baryon number, new CP violation in an extended Higgs sector and a first-order Electroweak phase transition catalyzed by extra scalar fields. Explicit baryon number violation exists in supersymmetric models with R-parity violation. Another popular scenario is producing an asymmetry in a dark sector which is then transferred into the visible sector, which may not require explicit B or L violation.

Experimentally, there are only a few observations that drive these BSM models. There is, of course, the size of the asymmetry itself. We also know that the asymmetry must have been produced by the time of BBN, at a temperature of order a few MeV. For models that use a long-lived particle to produce the asymmetry, this puts an upper bound on the particle's lifetime, $c\tau \lesssim 10^8$ meters. In leptogenesis models, a lepton asymmetry must be produced before Electroweak symmetry breaking so that sphalerons are still active. The size of new CP-violating interactions required to produce the asymmetry is very much model-dependent. As mentioned, the CKM phase, although *large*, is suppressed by small Yukawa couplings and is insufficient. On the other hand, in the absence of any dilution the new CP violation need not be large to produce an asymmetry of $O(10^{-10})$. If the model uses a first-order Electroweak phase transition, light ~~scalars,~~ $O(100$ GeV) mass, which mixes with the Higgs boson are required.

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B violation	CP violation	Out of equilibrium
Sphalerons	new CP violation in quarks	Cosmological phase transitions
Explicit B violation	new CP violation in leptons	out-of-equilibrium decays
Explicit L violation	new CP violation in scalars	*chemical potential*
Some other particle-number violation	CP violation in a dark sector	

TABLE I: BSM ingredients evoked to explain the BAU.

II. NEW THEORY DEVELOPMENTS

Although the question of generating the BAU has been around for several decades, particle theorists are still coming up with novel ways to address this mystery. While the vast majority of traditional baryogenesis models have involved high-scale physics and hence are difficult to probe experimentally. On the other hand many new BSM models produce the BAU at low-scales and are therefore experimentally observable. Indeed many of these new and exciting models are expected to produce signals at multiple experiments allowing for a multi-prong search for new physics. A necessarily incomplete list of examples of these new models include baryogenesis via particle–antiparticle oscillations in the early Universe [6–11], Axiogenesis [12], baryogenesis via late out-of-equilibrium decays of hidden sector gauginos [13].

It is important to point out the under-explored avenues in our understanding of the BAU. For instance, could we be missing any new kinds of CP violation, *e.g.* in the dark sector? Could there be new out-of-equilibrium mechanisms beyond Electroweak phase transition, *e.g.* QCD phase transition?

III. EXPERIMENTAL CONNECTIONS

As one of the strongest implications for new physics beyond the SM, the question of explaining the BAU should be integral to our experimental efforts within the high energy physics community. Furthermore the many parts of the BSM physics requirements of this problem requires a multi-pronged experimental approach. Below we give some examples of such experimental observables. However we emphasize that this categorization hides the cases where one experiment can be probing multiple facets of the generation of the BAU.

B or L violation. There has been claims that sphaleron processes could be observed at a 100 TeV collider, although this claim is not settled theoretically [14] (note also that sphaleron transitions are non-perturbative processes and require lattice calculations.) Explicit B and L violation could give rise to exotic decays at the LHC. Neutron-antineutron oscillation experiments can shed light on $\Delta B = 2$ processes, probing baryogenesis frameworks far beyond the reach of high energy colliders [15]. It is also worth pointing out that the possible existence of a lepton asymmetry in the universe is not yet established. An indirect way of probing baryogenesis models is to experimentally search for so-called washout processes (e.g. $\Delta L = 2$ processes). Their observation at the LHC or neutrinoless double beta decay [16, 17] can put high-scale baryogenesis models under tension.

CP violation. For certain EW baryogenesis models, new CP violation generates electric dipole moments (EDMs) for fermions and can be constrained by, *eg*, electron EDM experiments [18]. Measurement of the CP phase in the PMNS matrix is important for certain leptogenesis models. There are BSM models that predict CP-violating observables at the LHC or at B factories [8–11].

Out of equilibrium processes. Models with cosmological phase transitions often have an extended Higgs sector and this new physics can be searched for and constrained by collider experiments. Measuring the triple-Higgs coupling is one of the main efforts to exclude classes of multi-Higgs models as an explanation of the BAU. The non-observation of light stops already makes the MSSM incapable of producing this asymmetry. Observation of light scalars, often a necessary condition of a cosmological first-order phase transition, does not, however, unambiguously prove that such a phase transition occurred in the early universe. Such proof can be achieved by next generation, space-based gravitational wave detectors [19]. Alternative to a phase transition, many models use the out-of-equilibrium decay of a long-lived particle. These new particles necessarily interact with the SM and decay to either SM quarks or leptons, raising the prospect of producing and detecting them at particle colliders. Ongoing LLP searches at the LHC and new detectors like FASER, MATHUSLA, CODEX-b, etc can be used to search for such new particles.

Given the wide range of new testable models that could explain the baryon asymmetry, we think that this topic is important to include in a Snowmass white paper and has relevance for TE8, TE9, CF7, NF3, EF9, and RF4.

[1] N. Aghanim *et al.* (Planck), (2018), arXiv:1807.06209 [astro-ph.CO].

[2] A. D. Sakharov, Pisma Zh. Eksp. Teor. Fiz. **5**, 32 (1967), [Usp. Fiz. Nauk161,61(1991)].
[3] P. B. Arnold and L. D. McLerran, Phys. Rev. D **36**, 581 (1987).
[4] P. B. Arnold, D. Son, and L. G. Yaffe, Phys. Rev. D **55**, 6264 (1997), arXiv:hep-ph/9609481.
[5] K. Abe *et al.* (T2K), Nature **580**, 339 (2020), [Erratum: Nature 583, E16 (2020)], arXiv:1910.03887 [hep-ex].
[6] S. Ipek and J. March-Russell, Phys. Rev. D **93**, 123528 (2016), arXiv:1604.00009 [hep-ph].
[7] A. Ghalsasi, D. McKeen, and A. E. Nelson, Phys. Rev. D **92**, 076014 (2015), arXiv:1508.05392 [hep-ph].
[8] G. Elor, M. Escudero, and A. Nelson, Phys. Rev. D **99**, 035031 (2019), arXiv:1810.00880 [hep-ph].
[9] G. Alonso-lvarez, G. Elor, A. E. Nelson, and H. Xiao, JHEP **03**, 046 (2020), arXiv:1907.10612 [hep-ph].
[10] K. Aitken, D. McKeen, T. Neder, and A. E. Nelson, Phys. Rev. D **96**, 075009 (2017), arXiv:1708.01259 [hep-ph].
[11] A. E. Nelson and H. Xiao, Phys. Rev. D **100**, 075002 (2019), arXiv:1901.08141 [hep-ph].
[12] R. T. Co and K. Harigaya, Phys. Rev. Lett. **124**, 111602 (2020), arXiv:1910.02080 [hep-ph].
[13] A. Pierce and B. Shakya, JHEP **06**, 096 (2019), arXiv:1901.05493 [hep-ph].
[14] S. H. H. Tye and S. S. C. Wong, Phys. Rev. D **92**, 045005 (2015), arXiv:1505.03690 [hep-th].
[15] C. Grojean, B. Shakya, J. D. Wells, and Z. Zhang, Phys. Rev. Lett. **121**, 171801 (2018), arXiv:1806.00011 [hep-ph].
[16] F. F. Deppisch, J. Harz, and M. Hirsch, Phys. Rev. Lett. **112**, 221601 (2014), arXiv:1312.4447 [hep-ph].
[17] F. F. Deppisch, J. Harz, M. Hirsch, W.-C. Huang, and H. Ps, Phys. Rev. D **92**, 036005 (2015), arXiv:1503.04825 [hep-ph].
[18] N. F. Bell, T. Corbett, M. Nee, and M. J. Ramsey-Musolf, Physical Review D **99** (2019), 10.1103/physrevd.99.015034.
[19] C. Caprini, M. Chala, G. C. Dorsch, M. Hindmarsh, S. J. Huber, T. Konstandin, J. Kozaczuk, G. Nardini, J. M. No, K. Rummukainen, and et al., Journal of Cosmology and Astroparticle Physics **2020**, 024024 (2020).