

Wash-In Leptogenesis

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(Received 25 November 2020; accepted 30 March 2021; published 20 May 2021)

We present a leptogenesis mechanism based on the standard type-I seesaw model that successfully operates at right-handed-neutrino masses as low as a few hundred TeV. This mechanism, which we dub *wash-in leptogenesis*, does not require any CP violation in the neutrino sector and can be implemented even in the regime of strong wash-out. The key idea behind wash-in leptogenesis is to generalize standard freeze-out leptogenesis to a nonminimal cosmological background in which the chemical potentials of all particles not in chemical equilibrium at the temperature of leptogenesis are allowed to take arbitrary values. This sets the stage for building a plethora of new baryogenesis models where chemical potentials generated at high temperatures are reprocessed to generate a nonvanishing $B - L$ asymmetry at low temperatures. As concrete examples, we discuss wash-in leptogenesis after axion inflation and in the context of grand unification.

DOI: 10.1103/PhysRevLett.126.201802

Introduction.—The cosmic imbalance between matter and antimatter [1,2] represents clear evidence for new physics beyond the standard model (SM). Early attempts to explain the baryon asymmetry of the Universe (BAU) related its origin to the CP -violating decays of heavy GUT particles in grand unified theories (GUTs) [3–7]. It was, however, soon realized that electroweak sphaleron processes [8] spoil this explanation. In the early Universe, sphalerons nonperturbatively wash out the baryon-plus-lepton number $B + L$, which is exactly the linear combination of charges generated during standard GUT baryogenesis. This observation subsequently led to the proposal of leptogenesis [9], which links the BAU to neutrino physics in the type-I seesaw extension of the SM [10–14] and which exploits the fact that sphalerons do not violate the baryon-minus-lepton number $B - L$. Indeed, during leptogenesis, the CP -violating decays of right-handed neutrinos (RHNs) N_I ($I = 1, 2, \dots$) first create a lepton asymmetry (and, hence, nonzero $B - L$), which is then converted by the SM interactions in the thermal bath, including sphalerons, to a baryon asymmetry.

Standard thermal leptogenesis requires very large RHN masses, $M_I \gtrsim 10^9$ GeV, in order to achieve sufficient CP

violation during RHN freeze-out [15,16]. This makes it hard to directly probe the RHN sector in experiments and leads to large radiative corrections to the mass of the SM Higgs boson, which aggravates the SM hierarchy problem for RHN masses above the Vissani bound $M_I \lesssim 10^7$ GeV [17,18]. In addition, standard leptogenesis is vulnerable to strong asymmetry wash-out, if the RHN Yukawa interactions with the SM lepton-Higgs pairs $\ell_\alpha \phi$ are too strong [19–22].

In this Letter, we will present a mechanism to generate nonzero $B - L$ charge in the type-I seesaw model that avoids most of these shortcomings; for alternative routes to low-scale leptogenesis, see [23–30]. The key idea behind our proposal is to generalize standard freeze-out leptogenesis to a nonminimal cosmological background in which all conserved charges C at the time of leptogenesis (see Table I) are allowed to take arbitrary values. In such a background, the lepton-number-violating (LNV) RHN interactions then result in a new equilibrium attractor for the chemical potentials in the plasma that generically features nonzero $B - L$, even if $B - L = 0$ initially. The RHN interactions also actively drive the plasma toward this new attractor solution, which is why we dub our mechanism wash-in leptogenesis.

As we will show, wash-in leptogenesis can successfully operate down to RHN masses of a few hundred TeV, i.e., masses shortly above the equilibration temperature of the electron Yukawa interaction [31]. The mechanism, therefore, allows one to satisfy the Vissani bound; in particular, it

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TABLE I. Decoupling of SM interactions and associated conserved charges q_C . Yukawa interactions are denoted by y_i and weak (strong) sphalerons by WS (SS). The \checkmark symbol marks efficient interactions. Hypercharge and the Δ_α asymmetries are always preserved in the SM.

	$T[\text{GeV}]$	y_e	y_{ds}	y_d	y_s	y_{sb}	y_μ	y_c	y_τ	y_b	WS	SS	y_l
(v)	$(10^5, 10^6)$	q_e	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark
(iv)	$(10^6, 10^9)$	q_e	$q_{2B_1-B_2-B_3}$	q_{u-d}	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark
(iii)	$(10^9, 10^{11-12})$	q_e	$q_{2B_1-B_2-B_3}$	q_{u-d}	q_{d-s}	$q_{B_1-B_2}$	q_μ	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark
(ii)	$(10^{11-12}, 10^{13})$	q_e	$q_{2B_1-B_2-B_3}$	q_{u-d}	q_{d-s}	$q_{B_1-B_2}$	q_μ	q_{u-c}	q_τ	q_{d-b}	q_B	\checkmark	\checkmark
(i)	$(10^{13}, 10^{15})$	q_e	$q_{2B_1-B_2-B_3}$	q_{u-d}	q_{d-s}	$q_{B_1-B_2}$	q_μ	q_{u-c}	q_τ	q_{d-b}	q_B	q_u	\checkmark

is compatible with the neutrino option, which denotes the idea that RHNs with masses of a few PeV are responsible for radiatively generating the electroweak scale in the SM [32–36]. Wash-in leptogenesis is also independent of the amount of CP violation in the RHN sector, which liberates it from the Davidson-Ibarra bound $M_I \gtrsim 10^9$ GeV; and its success is not jeopardized by large Yukawa couplings. In fact, in the presence of additional conserved charges, strong asymmetry wash-out turns into efficient asymmetry wash-in.

Our proposal builds on earlier work, which already partly considered some of the ideas presented here [37–41] (see also [42]). The essential new elements of our analysis are the following: (i) We provide a systematic discussion spanning ten orders of magnitude in temperature, $T \in (10^5, 10^{15})$ GeV. In doing so, we account for all possible unconstrained charges in each temperature regime, which allows us to develop a general toolkit for constructing new baryogenesis models; see our main results in Table II. (ii) We pay particular attention to flavor. That is, we allow for an arbitrary flavor composition of the primordial charge asymmetries, and we take into account charged-lepton flavor effects in our analysis of wash-in leptogenesis. This especially includes effects related to flavor coherence or decoherence. (iii) We go beyond LNV two-to-two scattering processes mediated by the

dimension-5 Weinberg operator, considering also the ordinary decays and inverse decays of dynamical RHNs.

While wash-in leptogenesis can provide the basis for numerous new baryogenesis models, it does not represent a complete model by itself. It should rather be regarded as a general mechanism that describes how RHN interactions reprocess primordial charge asymmetries that were generated at higher temperatures. This includes the intriguing possibility of creating a nonvanishing $B - L$ asymmetry from $B - L$ -symmetric initial conditions. But it is agnostic about the ultraviolet (UV) physics that is responsible for setting these initial conditions. This is an advantage, as it allows us to perform a model-independent analysis from a bottom-up perspective. The remainder of this Letter is therefore organized as follows: First, we will study wash-in leptogenesis in the spirit of an effective field theory that describes the evolution of its input parameters (i.e., the primordial charge asymmetries) from some high-energy matching scale down to low energies. Then, we will turn to concrete UV completions that illustrate how wash-in leptogenesis can successfully create the BAU, even if $B - L = 0$ initially. Specifically, we will consider the generation of nonzero $B + L$ charge during GUT baryogenesis and axion inflation [44–47]. A lesson from these examples is that wash-in leptogenesis is able to resurrect baryogenesis scenarios that would otherwise suffer from

 TABLE II. Numerical coefficients x_C that describe the composition of $\mu_{B-L}^{\text{eq}} = q_{B-L}^{\text{eq}} 6/T^2$ in terms of the conserved charges $\mu_C = q_C 6/T^2$ in different temperature regimes; see Eq. (15). The \times symbol marks the absence of the corresponding μ_C due to an efficient SM interaction. The second column indicates the active flavors ℓ_α with respect to N_1 interactions; see the discussion around Eq. (13). The last column contains n_{Δ_\perp} , which vanishes in the case of $B - L$ -symmetric initial conditions. P and P_τ are model dependent and encode the flavor composition of the primordial $q_{e,\mu,\tau}$ asymmetries with respect to the N_1 wash-out direction [see the text for examples and Eqs. (S41) and (S56) [43]]. In this table and throughout the Letter, we assume vanishing global hypercharge, $\mu_Y = 0$. For more details, see Supplemental Material [43].

$T_{B-L}[\text{GeV}]$	Index α	μ_e	$\mu_{2B_1-B_2-B_3}$	μ_{u-d}	μ_{d-s}	$\mu_{B_1-B_2}$	μ_μ	μ_{u-c}	μ_τ	μ_{d-b}	μ_B	μ_u	μ_{Δ_\perp}
(v)	$(10^5, 10^6)$	e, μ, τ	$-\frac{3}{10}$	\times	\times	\times	\times	\times	\times	\times	\times	\times	\times
(iv)	$(10^6, 10^9)$	e, μ, τ	$-\frac{3}{17}$	0	$-\frac{7}{17}$	\times	\times	\times	\times	\times	\times	\times	\times
(iii)	$(10^9, 10^{11-12})$	\parallel_τ, τ	$(142 - 225P_\tau)/247$	0	$-\frac{123}{247} - \frac{82}{247}$	$\frac{123}{494}$	$(142 - 225P_\tau)/247$	\times	\times	\times	\times	\times	$\frac{225}{247}$
(ii)	$(10^{11-12}, 10^{13})$	\parallel	$(-23P + 7)/30$	$\frac{1}{5}$	$-\frac{3}{5}$	$-\frac{1}{6}$	$-\frac{3}{10}$	$(-23P + 7)/30$	$\frac{3}{10}$	$(-23P + 7)/30$	$-\frac{4}{15}$	$\frac{23}{90}$	\times
(i)	$(10^{13}, 10^{15})$	\parallel	$(-3P + 1)/4$	$\frac{1}{6}$	$-\frac{5}{6}$	$-\frac{1}{4}$	$-\frac{1}{4}$	$(-3P + 1)/4$	$\frac{1}{4}$	$(-3P + 1)/4$	$-\frac{1}{3}$	$\frac{1}{6}$	$\frac{1}{3}$

strong asymmetry wash-out, in a way that is more complex than simply resorting to standard leptogenesis.

Wash-in leptogenesis.—We begin by considering a particularly interesting and simple scenario: N_1 -dominated wash-in leptogenesis at temperatures of a few hundred TeV. In this temperature regime, all SM interactions are equilibrated—except for the electron Yukawa interaction, which renders the comoving charge asymmetry of right-handed electrons a classically conserved quantity, $q_e/s = \text{const}$, with entropy density s . Its anomalous violation via the chiral plasma instability is negligibly slow for the q_e/s values of interest [48–50]. At the same time, all charged-lepton flavors $\alpha = e, \mu, \tau$ are fully decohered, which allows us to work with the standard Boltzmann equations for the three lepton flavor asymmetries $\Delta_\alpha = B/3 - L_\alpha$ in the type-I seesaw model [24,26]:

$$-(\partial_t + 3H)q_{\Delta_\alpha} = \varepsilon_{1\alpha}\Gamma_1(n_{N_1} - n_{N_1}^{\text{eq}}) - \sum_\beta \gamma_{\alpha\beta}^w \frac{\mu_{\ell_\beta} + \mu_\phi}{T}, \quad (1)$$

which is valid in the nonrelativistic regime $T \lesssim M_1$, where any N_1 chemical potential is clearly negligible because of the N_1 Majorana mass $\mu_{N_1} \simeq 0$. The negative sign on the left-hand side follows from $\Delta_\alpha \supset -L_\alpha$. The charge asymmetry q_i for a particle species i is defined as the difference of its particle and antiparticle number densities, $q_i = n_i - n_{\bar{i}} = g_i \mu_i T^2/6$, with chemical potential μ_i and multiplicity g_i , while $q_C = \mu_C T^2/6$ for all conserved charges C , with μ_C in Eq. (5). The first term on the right-hand side in Eq. (1) is the standard source term describing the asymmetry production from RHN decays, while the second term is the standard wash-out term, with total wash-out rate per unit volume

$$\gamma_{\alpha\beta}^w = \gamma_{\alpha\beta}^{\text{id}} + \sum_\sigma [(\delta_{\alpha\beta} + \delta_{\sigma\beta})\gamma_{\alpha\sigma}^{\Delta L=2} + (\delta_{\alpha\beta} - \delta_{\sigma\beta})\gamma_{\alpha\sigma}^{\Delta L=0}], \quad (2)$$

which encompasses RHN inverse decays $\gamma_{\alpha\beta}^{\text{id}} = \gamma_{1\alpha}\delta_{\alpha\beta}$ as well as $\Delta L = 2$ and lepton-flavor-violating $\Delta L = 0$ two-to-two scattering processes (see [24,26] for more details).

Before we are able to solve the coupled system of equations in Eq. (1), we have to specify the relation among the chemical potentials μ_{ℓ_α} , μ_ϕ , and μ_{Δ_α} . In standard leptogenesis, this relation is encoded in the flavor coupling matrix $(\underline{C})_{\alpha\beta} = C_{\alpha\beta}$ [51–56], whose structure is determined by SM spectator processes [57–59]. The crucial difference between standard leptogenesis and our scenario is that, in a nontrivial chemical background, the standard *linear* relation $\mu_{\ell_\alpha} + \mu_\phi = -\sum_\beta C_{\alpha\beta}\mu_{\Delta_\beta}$ turns into an *affine* relation:

$$\mu_{\ell_\alpha} + \mu_\phi = \mu_\alpha^0 - \sum_\beta C_{\alpha\beta}\mu_{\Delta_\beta}, \quad (3)$$

where, at temperatures of a few hundred TeV, the translation by the constant shift vector μ_α^0 is solely induced by the conserved chemical potential of the right-handed electrons:

$$\begin{pmatrix} \mu_{\ell_e} + \mu_\phi \\ \mu_{\ell_\mu} + \mu_\phi \\ \mu_{\ell_\tau} + \mu_\phi \end{pmatrix} = \begin{pmatrix} -\frac{5}{13} \\ \frac{4}{37} \\ \frac{4}{37} \end{pmatrix} \mu_e - \begin{pmatrix} \frac{6}{13} & 0 & 0 \\ 0 & \frac{41}{111} & \frac{4}{111} \\ 0 & \frac{4}{111} & \frac{41}{111} \end{pmatrix} \begin{pmatrix} \mu_{\Delta_e} \\ \mu_{\Delta_\mu} \\ \mu_{\Delta_\tau} \end{pmatrix}. \quad (4)$$

Equations (3) and (4) follow from analyzing all 16 SM chemical potentials μ_i ($i = e, \mu, \tau, \ell_e, \ell_\mu, \ell_\tau, u, c, t, d, s, b, Q_1, Q_2, Q_3, \phi$): In any given temperature regime, the number of linearly independent conserved charges C and the number of SM interactions in equilibrium always add up to 16; see Table I. This results in 16 constraint equations in each temperature regime that allow one to express the chemical potentials μ_i of all SM species as linear combinations of the conserved chemical potentials μ_C ($C = \Delta_\alpha, \dots$). In general, we therefore obtain a constant shift vector μ_α^0 in Eq. (3) of the form

$$\mu_\alpha^0 = \sum_{C \neq \Delta_\alpha} S_{\alpha C} \mu_C, \quad \mu_C = \sum_i n_i^C g_i \mu_i, \quad (5)$$

with charge vectors n_i^C and multiplicities g_i ; see [60] for details. We provide explicit expressions for n_i^C , g_i , the flavor coupling matrices $C_{\alpha\beta}$, and source matrices $S_{\alpha C}$ in all temperature regimes of interest in Supplemental Material [43].

Equations (1) and (3) tell us that the Boltzmann equations are linear in the lepton flavor asymmetries Δ_α . This allows us to split q_{Δ_α} into contributions from thermal and wash-in leptogenesis, respectively, $q_{\Delta_\alpha} = q_{\Delta_\alpha}^{\text{th}} + q_{\Delta_\alpha}^{\text{win}}$, such that

$$(\partial_t + 3H)q_{\Delta_\alpha}^{\text{win}} = \sum_\beta \Gamma_{\alpha\beta}^w \left(q_\beta^0 - \sum_\sigma C_{\beta\sigma} q_{\Delta_\sigma}^{\text{win}} \right), \quad (6)$$

where $\Gamma_{\alpha\beta}^w = 6/T^3 \gamma_{\alpha\beta}^w$. Equation (6) is reminiscent of spontaneous baryogenesis [61,62], specifically, spontaneous leptogenesis [63,64], where the rolling of a (pseudo) scalar field φ induces effective chemical potentials $\mu_\alpha^0 \propto q_\alpha^0$ [60] (see also [65,66]). The difference between spontaneous leptogenesis and our scenario is that we assume nonzero primordial asymmetries stored in a set of conserved charges, whereas spontaneous leptogenesis involves time-dependent asymmetries—controlled by the interaction Lagrangian of the field φ and not necessarily related to conserved charges—that are present only when φ is in motion. This requires that LNV processes must be efficient exactly at the time when φ is rolling. In our scenario, such a temporal coincidence is not needed. Still, it is

straightforward to generalize the following analysis to time-dependent charges q_α^0 [67].

At any given temperature, the total wash-out rate is typically dominated by a single process, such that it factorizes into $\Gamma_{\alpha\beta}^w = P_{\alpha\beta}\Gamma_w$, where the temperature dependence is contained in the flavor-blind wash-out rate Γ_w and where the matrix $(\underline{P})_{\alpha\beta} = P_{\alpha\beta}$ encodes the flavor structure. In this case, it is then possible to write down an exact solution of Eq. (6). For arbitrary initial conditions $q_{\Delta\beta}^{\text{ini}}$, we find

$$q_{\Delta\alpha}^{\text{win}} = \sum_{\beta} (\delta_{\alpha\beta} - E_{\alpha\beta}) q_{\Delta\beta}^{\text{eq}} + \sum_{\beta} E_{\alpha\beta} q_{\Delta\beta}^{\text{ini}} \frac{s}{s^{\text{ini}}}. \quad (7)$$

$q_{\Delta\alpha}^{\text{eq}}$ is the equilibrium attractor in the presence of RHNs,

$$q_{\Delta\alpha}^{\text{eq}} = \sum_{\beta} C_{\alpha\beta}^{-1} q_{\beta}^0 = \sum_{\beta} \sum_{C \neq \Delta_\alpha} C_{\alpha\beta}^{-1} S_{\beta C} q_C, \quad (8)$$

which can also be derived from Eq. (3) by requiring all RHN interactions to be in equilibrium, $\mu_{\ell_\alpha} + \mu_\phi = \mu_{N_1} = 0$. The matrix $(\underline{E})_{\alpha\beta} = E_{\alpha\beta}$ describes how the RHN interactions actively drive the plasma exponentially close to this solution:

$$\underline{E} = \exp(-wK_1\underline{P}\underline{C}), \quad w = \frac{1}{K_1} \int_0^\infty dz \frac{\Gamma_w}{zH}, \quad z = \frac{M_1}{T}, \quad (9)$$

where K_1 denotes the standard N_1 decay parameter:

$$K_1 = \frac{\Gamma_1(T=0)}{H(T=M_1)}. \quad (10)$$

At temperatures of a few hundred TeV, the total wash-out rate is dominated by inverse decays, such that $P_{\alpha\beta} = p_{1\alpha}\delta_{\alpha\beta}$ and

$$\underline{E} = \exp(-wK_1\underline{C}_1), \quad (\underline{C}_1)_{\alpha\beta} = p_{1\alpha}C_{\alpha\beta}, \quad p_{1\alpha} = \frac{\Gamma_{1\alpha}}{\Gamma_1}, \quad (11)$$

where $w \approx 3\pi/4$ assuming Maxwell-Boltzmann statistics for all particles [68]. For strong wash-in, $K_1 \gg 1$, and a generic flavor structure, $p_{1\alpha} \ll 1$, all entries of \underline{E} are exponentially suppressed. The total washed-in $B-L$ asymmetry then reads

$$q_{B-L}^{\text{win}} \simeq q_{B-L}^{\text{eq}} = \sum_{\alpha} q_{\Delta\alpha}^{\text{eq}} = -\frac{3}{10} q_e, \quad (12)$$

which also immediately follows from Eq. (4). Any UV mechanism that results in $q_e \neq 0$ at high temperatures, thus, induces nonzero $B-L$ at temperatures of a few hundred TeV.

Flavor effects.—Next, let us generalize the above discussion to arbitrary temperatures $T \in (10^5, 10^{15})$ GeV. Equations (1)–(9), except for Eq. (4), remain valid in this case, the only difference being that the meaning of the flavor index α is now different. At $T \in (10^9, 10^{11-12})$ GeV, electrons and muons propagate as coherent states, which means $\alpha = \parallel_\tau, \tau$, while at temperatures $T \in (10^{11-12}, 10^{15})$ GeV, all three charged leptons propagate in coherent superpositions, such that $\alpha = \parallel$. Here, ℓ_\parallel represents the coherent single-flavor field that can be created and destroyed by N_1 interactions, and $\ell_{\parallel\tau}$ is the same field after projecting out its τ component. Denoting the N_1 Yukawa couplings by h_1^e, h_1^μ , and h_1^τ , we can write

$$h_\parallel \ell_\parallel = h_1^e \ell_e + h_1^\mu \ell_\mu + h_1^\tau \ell_\tau, \quad h_{\parallel\tau} \ell_{\parallel\tau} = h_1^e \ell_e + h_1^\mu \ell_\mu, \quad (13)$$

where $h_\parallel^2 = |h_1^e|^2 + |h_1^\mu|^2 + |h_1^\tau|^2$ and $h_{\parallel\tau}^2 = |h_1^e|^2 + |h_1^\mu|^2$. Flavor coherence at higher temperatures also implies that some flavor asymmetry Δ_\perp can escape wash-in leptogenesis:

$$\Delta_\perp = \begin{cases} B/3 - L_\perp, & T \in (10^9, 10^{11-12}) \text{ GeV}, \\ 2B/3 - L_{\perp_1} - L_{\perp_2}, & T \in (10^{11-12}, 10^{15}) \text{ GeV}, \end{cases} \quad (14)$$

where ℓ_\perp is perpendicular to ℓ_τ and $\ell_{\parallel\tau}$ and where ℓ_{\perp_1} and ℓ_{\perp_2} span the two-dimensional flavor space perpendicular to ℓ_\parallel . Making use of these definitions and assuming again strong wash-in and generic RHN couplings, Eq. (12) now turns into

$$q_{B-L}^{\text{eq}} = \sum_{C \neq \Delta_\alpha} x_C q_C, \quad x_C = \delta_{C\Delta_\perp} + \sum_{\alpha,\beta} C_{\alpha\beta}^{-1} S_{\beta C}, \quad (15)$$

where the numerical coefficients x_C are listed in Table II. This asymmetry remains conserved as soon as the RHN interactions become inefficient at some high temperature T_{B-L} [22]. We therefore obtain for the present-day BAU

$$\left. \frac{q_B}{s} \right|_{\text{today}} = c_{\text{sph}} \left. \frac{q_{B-L}^{\text{th}} + q_{B-L}^{\text{win}}}{s} \right|_{T_{B-L}}, \quad (16)$$

where $c_{\text{sph}} \simeq 12/37$ [69]. Note that the standard contribution from thermal leptogenesis may be suppressed because of strong wash-out or insufficient CP violation.

Equation (15) and Table II are our main results, which serve as a general toolkit to construct new baryogenesis models by implementing the following algorithm: (i) Conceive a UV model that leads to primordial chemical potentials μ_i for some particle species i . (ii) Determine the corresponding conserved charges μ_C . (iii) Specify the N_1 mass and, hence, relevant temperature scale for

leptogenesis, T_{B-L} . (iv) Compute the final BAU according to Eqs. (15) and (16).

Possible UV completions.—Let us now showcase two possibilities for generating primordial charge asymmetries prior to wash-in leptogenesis. Both scenarios result in $B + L \neq 0$ but preserve $B - L$. First, we consider SU(5) unification, where the decay of the heavy colored Higgs field $H^c \subset \mathbf{5}$ mainly proceeds via the third-generation Yukawa coupling, $H^c \rightarrow \bar{Q}_3 \bar{Q}_3, t\tau, Q_3 \ell_\tau, \bar{t} \bar{b}$ [7,70,71]. The production and decay of H^c bosons after inflation in the SU(5)-broken phase (see, e.g., Refs. [72,73] for a viable scenario) then results in $\mu_{Q_3} = \mu_{\ell_\tau} = -\mu_\tau = \mu_0$, $\mu_t = -2\mu_0/3$, and $\mu_b = -\mu_0/3$ or, equivalently, $\mu_B = -\mu_{2B_1-B_2-B_3} = \mu_{\ell_\tau} = -\mu_\tau = 3\mu_{d-b} = \mu_0$, while all other chemical potentials vanish. Here, μ_0 is determined by the decay rate, CP violation, and production mechanism of the colored Higgs field. This scenario sets the stage for wash-in leptogenesis above the equilibration temperature of the tau Yukawa interaction, $T \gtrsim 10^{11-12}$ GeV. Similarly, one can construct models where extra Higgs scalars also generate primordial asymmetries in the first two fermion generations. The initial $q_{e,\mu,\tau}$ asymmetries are then encoded in general fields $\bar{e} = c_e e + c_\mu \mu + c_\tau \tau$ or $\bar{e}_\tau = c_e^* e + c_\mu^* \mu$, such that

$$P = |a_e c_e^* + a_\mu c_\mu^* + a_\tau c_\tau^*|^2, \quad P_\tau = |b_e c_e^* + b_\mu c_\mu^*|^2 \quad (17)$$

in Table II, where $a_{e,\mu,\tau} = h_1^{e,\mu,\tau}/h_{\parallel}$ and $b_{e,\mu} = h_1^{e,\mu}/h_{\parallel\tau}$.

Our second example is axion inflation featuring a coupling of the axion-inflaton field φ to the Chern-Simons term of the hypercharge gauge field, $\varphi/(4\Lambda)Y_{\mu\nu}\tilde{Y}^{\mu\nu}$ [74]. This coupling sources nonvanishing $\langle Y_{\mu\nu}\tilde{Y}^{\mu\nu} \rangle$ during inflation [75–77], which induces primordial chemical potentials for all SM fermion species via the SM chiral anomaly [78,79], $\mu_i/T = \pm 3(n_i^Y)^2 \alpha_Y / \pi (h_Y/T^3)_{\text{rh}}$ [46,47], with hypercharge fine-structure constant α_Y , hypercharges n_i^Y , and \pm for left- and right-handed fermions. $h_Y = \langle \mathbf{A}_Y \cdot \mathbf{B}_Y \rangle / a^3$ is the physical hypermagnetic helicity density, which is defined in terms of the comoving vector potential \mathbf{A}_Y , comoving flux density \mathbf{B}_Y , and cosmic scale factor a . In the parameter region where h_Y/T^3 is approximately conserved [47,80–82], its value at reheating after inflation dictates the magnitude of the conserved charges in each temperature regime. For $T \in (10^5, 10^6)$ GeV, e.g., we have $\mu_e/T = -3\alpha_Y / \pi (h_Y/T^3)_{\text{rh}}$ and, hence, $\mu_{B-L}/T = 9/10 \alpha_Y / \pi (h_Y/T^3)_{\text{rh}}$. Axion inflation with a Hubble rate of $H_{\text{inf}} \sim 10^{10}$ GeV can therefore readily give rise to the observed baryon asymmetry [47]. The evolution of B and L in this scenario is schematically shown in Fig. 1. Axion inflation produces all lepton flavors in a symmetric way, meaning $P = 1/3$ and $P_\tau = 1/2$ in Table II.

Conclusions.—In this Letter, we presented a systematic discussion of wash-in leptogenesis, a mechanism to generate nonzero $B - L$ in the type-I seesaw model. Our mechanism successfully operates at low RHN masses,

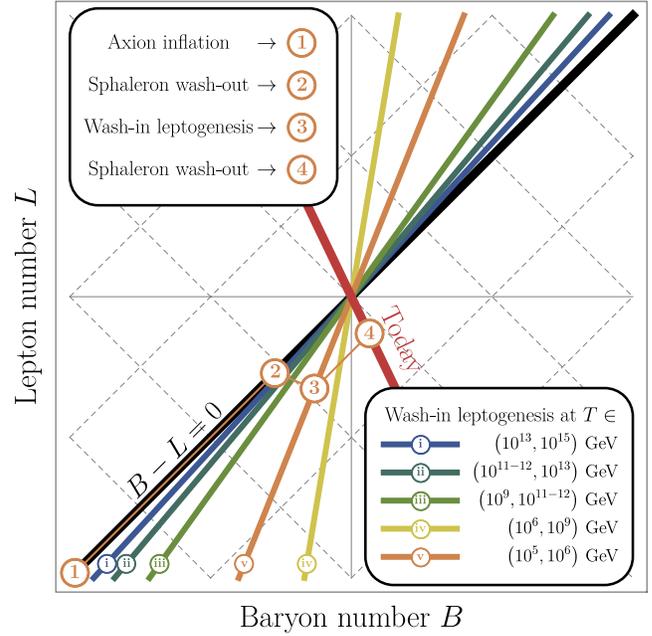


FIG. 1. Schematic evolution of B and L in arbitrary units after axion inflation. The colorful straight lines represent the equilibrium attractors of wash-in leptogenesis in different temperature regimes.

strong wash-out, negligible CP violation in RHN decays, and $B - L$ -symmetric initial conditions. We focused on N_1 -dominated wash-in leptogenesis; however, the inclusion of heavy-neutrino flavor effects [83], or even the generalization to a density-matrix formalism [84–86], is straightforward. Similarly, one may generalize our mechanism to other sources of LNV in the early Universe. The general concept of wash-in leptogenesis opens the door to a plethora of possibilities.

We thank Apostolos Pilaftsis, Mikhail Shaposhnikov, and Daniele Teresi for helpful comments. K. K. was supported by JSPS KAKENHI, Grant-in-Aid for Scientific Research No. JP19K03842 and Grant-in-Aid for Scientific Research on Innovative Areas No. 19H04610. K. M. was supported by Deutsche Forschungsgemeinschaft under Germany’s Excellence Strategy—EXC 2121 Quantum Universe—390833306. M. Y. was supported by the Leading Initiative for Excellent Young Researchers, Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan, and by JSPS KAKENHI Grants No. 20H05851, No. 21K13910, and No. JP20K22344. This project has received funding from the European Union’s Horizon 2020 Research and Innovation Program under Grant Agreement No. 796961, “AxiBAU” (K. S.).

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