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Matter and antimatter in the universe

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Abstract. We review observational evidence for a matter–antimatter asymmetry in the early universe, which leads to the remnant matter density we observe today. We also discuss bounds on the presence of antimatter in the present-day universe, including the possibility of a large lepton asymmetry in the cosmic neutrino background. We briefly review the theoretical framework within which baryogenesis, the dynamical generation of a matter–antimatter asymmetry, can occur. As an example, we discuss a testable minimal particle physics model that simultaneously explains the baryon asymmetry of the universe, neutrino oscillations and dark matter.

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Contents

1. Introduction

The existence of antimatter is a direct consequence of combining two of the most fundamental known concepts in physics, the theory of relativity and quantum mechanics. Its theoretical prediction, based on these abstract principles [1], and experimental discovery [2] represent one of the great successes of theoretical physics. At the time of its discovery, antimatter was thought to be an exact mirror of matter; all phenomena that had been observed in nature were invariant under conjugation of parity (P) and charge (C) as well as time reversal (T), and not much was known about the early history of the universe. Henceforth, the enormous matter–antimatter asymmetry of the nearby universe (complete absence of antimatter except in cosmic rays) posed a mystery that could only be explained by assuming that the universe was set up like this.

With the rise of the big bang theory after the theoretical prediction [3, 4] and observational discovery of the cosmic expansion [5] and cosmic microwave background (CMB) [6], it became clear that the universe was hot during the early stages of its history [7], and antimatter was present when pair-creation and annihilation reactions were in thermal equilibrium. When particle energies in the cooling plasma became too small for pair creation, almost all particles and antiparticles were annihilated, with a small amount of matter (by definition) surviving. The baryon asymmetry of the universe (BAU) can be defined as the difference between the number of baryons N_B and antibaryons $N_{\bar{B}}$ divided by their sum (or the entropy s) just before antiprotons disappeared from the primordial plasma. Since the end products of annihilation processes are mostly photons and there are no antibaryons in the universe today[5], the BAU can be estimated by the baryon to photon ratio η,

$$\eta = \frac{N_B}{N_\gamma}\Big|_{T=3\,\mathrm{K}} = \frac{N_B - N_{\bar{B}}}{N_\gamma}\Big|_{T=3\,\mathrm{K}} \sim \frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}}\Big|_{T\gtrsim 1\,\mathrm{GeV}}. \tag{1}$$

[5] Here we assume that the BAU is the same everywhere in space within the observable universe, we discuss this point in section 2.

η is related to the remnant density of baryons Ω_B, in units of the critical density, by $\Omega_B \simeq \eta/(2.739 \times 10^{-8} h^2)$, where h parameterizes the Hubble rate $H_0 = 100\,h$ (km s^{-1} Mpc^{-1}. It can be determined independently in two different ways, from the abundances of light elements in the intergalactic medium (IGM), see section 3.1, and from the power spectrum of temperature fluctuations in the CMB, see section 3.2. Both consistently give values $\sim 10^{-10}$; the precise numbers are given in section 3. Thus, today's huge matter–antimatter asymmetry was actually a tiny number in the past. The discovery of small violations of P [8] and CP [9] invariance (and thus also C invariance) provided hints that this asymmetry may have been created dynamically by *baryogenesis* from a matter–antimatter symmetric initial state.

There are three necessary conditions for successful baryogenesis, which were first formulated by Sakharov [10][6]: (i) baryon number violation, (ii) C and CP violation and (iii) a deviation from thermal equilibrium. Intuitively, these conditions can easily be understood. Without baryon number violation, it is not possible for any system to evolve from a state with baryon number $B = 0$ to a state with $B \neq 0$. If C (or CP) symmetry were to hold, for each process that generates a matter–antimatter asymmetry, there would be a C (or CP) conjugate process that generates an asymmetry with the opposite sign and occurs with the same probability. Finally, thermal equilibrium is a time translation invariant state in which the expectation values of all observables are constant, therefore it requires a deviation from equilibrium to evolve from $B = 0$ to $B \neq 0$. Formally, Sakharov's conditions can be proven by means of quantum mechanics and statistical physics. We describe the universe as a thermodynamic ensemble, characterized by a density matrix $\hat{\varrho}$. In the Schrödinger picture, $\hat{\varrho}$ evolves in time according to the von Neumann (or quantum Liouville) equation

$$\mathrm{i}\frac{\partial \hat{\varrho}(t)}{\partial t} = [\hat{H}, \hat{\varrho}(t)], \tag{2}$$

where $\hat{H}$ is the Hamiltonian. The baryon number is given by $B(t) = \mathrm{tr}(\hat{B}\hat{\varrho}(t))$, where $\hat{B}$ is the baryon number operator. If $[\hat{B}, \hat{H}] = 0$ and $B = 0$ at the initial time, then $B = 0$ at all times, which proves point (i). To prove point (ii), we consider an arbitrary discrete transformation $\hat{X}$ that commutes with $\hat{H}$ and anticommutes with $\hat{B}$. If $\hat{\varrho}(t)$ at some time t_0 is symmetric under $\hat{X}$, $[\hat{X}, \hat{\varrho}(t_0)] = 0$, then this holds for all times. Thus, in order to create a CP-asymmetric state from a symmetric initial state, $\hat{H}$ must not commute with $\hat{\mathrm{C}}\hat{\mathrm{P}}$. The proof of (iii) is trivial since in thermal equilibrium, $\hat{\varrho}^{\mathrm{eq}}$ is time translation invariant by definition; thus B is constant.

The paradigm of *cosmic inflation* [12] elevated the assumption of an initial state with $B = 0$ from an assumption, based on aesthetic reasoning, to a generic prediction. If the universe underwent a period of accelerated expansion during its very early history that lasted for long enough to explain its spatial flatness and the isotropy of the CMB temperature, any pre-existing baryon asymmetry was diluted and negligible at the end of inflation[7]. Therefore, baryogenesis needs to occur either during reheating or in the radiation-dominated epoch.

The Standard Model (SM) of particle physics and cosmology, in principle, fulfills all the three Sakharov conditions [13]. The baryon number is violated by sphaleron processes [13, 14], P and CP are violated by the weak interaction and the quark Yukawa couplings [15] and the non-equilibrium condition is fulfilled due to the expansion of the universe. As it turns out,

[6] See also [11] for a related early discussion.

[7] If B and L are violated individually, such as e.g. in the model presented in section 4.3 or thermal leptogenesis, a state with $B = 0$ is also reached unavoidably, even for an initial $B \neq 0$, when the universe reaches chemical equilibrium.

the smallness of the CP violation and current bounds on the mass of the Higgs particle make it extremely unlikely that successful baryogenesis is possible within the SM. The CP violation and deviation from equilibrium during electroweak symmetry breaking are both too small. These aspects are discussed in more detail in section 4.1. However, models of particle physics beyond the SM generally contain many new sources of CP and possibly B-violation, and a large number of baryogenesis scenarios are discussed in the literature.

The remainder of this paper is organized as follows. The following two sections are devoted to observational evidence for a matter–antimatter asymmetry in the universe. In section 2 we review bounds on the existence of primordial antimatter at the present time. We also discuss the possibility that there is no overall asymmetry in the universe, which is composed of regions dominated by matter or antimatter. We conclude that it is almost certain that all structures in the observable universe are composed of matter only[8]. In section 3 we adopt that viewpoint and review current measurements of the asymmetry parameter defined in (1). In section 3 we briefly overview theoretical approaches to explain the BAU, focusing on testable models. Finally, in section 4.3, we discuss a minimal model, in which all particles may be found using present-day observational and experimental techniques.

2. Antimatter in the present universe

The only place in the present-day universe where we can directly look for antimatter is the solar system, where we have visited and approached various celestial bodies with spacecraft. It does not contain any significant amount of antimatter[9]. We receive direct probes from other parts of our galaxy in the form of cosmic rays, which have recently been intensively studied by the PAMELA and FERMI space observatories. These contain a fraction of positrons and antiprotons, the only primary source of antimatter found outside the laboratory to date. However, since the pair-creation threshold for these particles is relatively low, they can be generated by various astrophysical processes and are expected to be found even in a universe that is entirely made of matter otherwise. If heavier antinucleids were found, this would indicate that there exist traces of antimatter within our own galaxy. So far, none have been discovered. The lack of findings by the first mission of the Alpha Magnetic Spectrometer (AMS) allows to conclude their absence at a level of 10^{-6} [19]. These bounds are expected to tighten after data from the AMS 02 experiment, currently mounted on the International Space Station (ISS), is released. Furthermore, in [18] it was argued that the fraction f of antimatter in the ISM cannot be larger than $f < 10^{-15}$ because the lifetime of antinuclei in the ISM due to annihilations is only 300 years [16].

Upper bounds on the presence of antimatter in other parts of the universe can be imposed by indirect detection methods. One can distinguish two basic scenarios: either matter and antimatter are mixed homogeneously, i.e. the interstellar medium (ISM) or IGM are matter dominated everywhere in space, but contain a certain fraction of antimatter[10], or patches of

[8] Here and in the following, 'matter' and 'antimatter' refer to baryons. We do not discuss the unknown composition and origin of dark matter (except in section 4.3), which in many popular models is not related to η.

[9] Antimatter in the solar system can also be excluded because it would lead to a strong signal when annihilating with solar winds [16].

[10] Such a mixing is not possible within individual stellar systems because the antimatter would have annihilated during the gravitational collapse that lead to their formation [16].

matter and antimatter coexist. In both cases one would expect to observe x-rays and γ-rays from annihilation processes.

2.1. A patchwork universe

If the universe is a patchwork of regions that are strongly dominated by either matter or antimatter, the question arises as to what is the typical size of such regions. The possibility of individual antimatter stellar systems has been discussed in [16, 18], see also [17]. The absence of annihilation signals from such stars passing through the ISM allows us to conclude that their fraction in the galaxy is $<10^{-4}$. Since the presence of such systems is hard to accommodate within a realistic model of galaxy formation, it is tempting to conclude that it is zero. Similar arguments can be brought forward against the possibility of clouds of antigas or other isolated objects in the milky way. This viewpoint has been questioned in [20], see also references therein. However, no definite conclusions that hint towards the opposite could be drawn. In [18] it was furthermore pointed out that the authors of [20] may have underestimated the annihilation cross sections at low energies.

This still leaves open the possibility that the universe is a patchwork of huge distinct regions of matter and antimatter, in the most extreme case with vanishing baryon number $B = 0$ when averaged over large volumes. If this were the case, these regions would have to be at least of comparable size as the observable universe [21, 22]. This conclusion can be drawn from the measured cosmic diffuse γ-ray (CDG) background. After nonlinear structure formation, the matter and antimatter domains may have been separated by sufficiently large voids in the IGM to suppress annihilation at the domain walls and avoid a detectable γ-ray flux. However, the homogeneity of the CMB does not allow for such spatial separation before recombination. Hence, matter and antimatter domains must have been in touch at least between the time of recombination and the beginning of nonlinear structure formation. The γ-rays produced by annihilation during this period would, although redshifted, still be present today and contribute to the CDG. The measured intensity of the CDG allows us to conclude that the domains must at least have a size comparable to the observable universe [21].

2.2. A mixed universe

The considerations at the beginning of this section strongly constrain diffuse antimatter within our galaxy. The fraction f of antimatter on larger scales is constrained by the measured γ-ray flux from the IGM. The IGM emits x-rays due to thermal bremsstrahlung in two-body collisions. The expected flux of γ-rays F_γ is proportional to the flux of x-rays F_X. This allows us to constrain f as [18]

$$f \leqslant 3 \times 10^{-11} \frac{T}{keV} \frac{F_\gamma}{F_X}, \tag{3}$$

where T is the gas temperature and the inequality is due to the fact that not all γ-rays originate from annihilations. In [18], the upper bounds on the γ-flux imposed by the EGRET space telescope [24] were used to constrain f for a sample of 55 galaxy clusters from the limited flux survey published in [25]. The obtained values scatter between $f < 5 \times 10^{-9}$ and $f < 10^{-6}$, indicating that these clusters consist either entirely of matter or antimatter in good approximation. Furthermore, if there are any antimatter-dominated regions, they must be separated from the matter domains at least by distances comparable to the size $\sim$Mpc of galaxy clusters. Observations of colliding galaxy clusters allow us to extend the analysis to even larger scales. For the bullet cluster [26], an upper bound of $f < 3 \times 10^{-6}$ was obtained in [18]. If representative, this allows us to extend the constraints on f to scales of tens of Mpc. In combination with the considerations in section 2.1, this indicates that the present-day observable universe most likely does not contain significant amounts of antimatter.

3. The baryon asymmetry of the universe

As motivated by the discussion in section 2, we in the following adopt the viewpoint that the universe is baryon asymmetric and the asymmetry is the same everywhere within the observable Hubble volume. Within the concordance model of cosmology (ΛCDM) [23], it can be estimated by the baryon to photon ratio (1). There are two independent ways of determining this parameter, from the relative abundances of light elements in the IGM on the one hand and from the spectrum of temperature fluctuations in the CMB on the other. Since they measure η at very different stages during the history of the universe, they also provide a check of the ΛCDM model itself.

3.1. Big bang nucleosynthesis

Throughout the evolution of the universe, there was a brief period during which the temperature was low enough for nuclei with mass number $A > 1$ to exist and still high enough for thermonuclear reactions to occur. This *big bang nucleosynthesis* (BBN) is thought to be the main source of deuterium (D), helium (^{3}He, ^{4}He) and lithium (mainly ^{7}Li) in the universe [7], see e.g. [27] for a review. These elements, in particular H and ^{4}He, make up the vast majority of all nuclei in the universe[11].

The processes relevant for BBN start when the temperature of the primordial plasma is around $T \sim 2\,\mathrm{MeV}$ with the neutrino freeze-out; that is, the reactions that keep neutrinos in equilibrium with the plasma become slower than the expansion of the universe. This energy range is easily accessible in the laboratory, and the underlying particle physics is well understood. Thus, in the standard scenario the sole unknown parameter that enters BBN is the baryon to photon ratio η, which was fixed by unknown physics (baryogenesis) at higher energies. For a given η, the time evolution of the different isotopes' abundances can be determined by solving a network of Boltzmann equations. Thus, within ΛCDM and the SM, η can be uniquely determined by measuring the primordial abundances of light elements. The result found in [28], in units of 10^{-10}, is

$$\eta_{\mathrm{SBBN}} = 5.80 \pm 0.27, \tag{4}$$

more constraining than the 95% CL value $4.7 < \eta_{\mathrm{SBBN}} < 6.5$ quoted in [27].

The good agreement with observational data allows us to impose tight constraints on theories of particle physics beyond the SM which predict charged or unstable thermal relics from an earlier epoch to be present around the time of BBN. Even without additional particles that participate in BBN reactions, non-standard physics may leave a trace in the abundances

[11] Heavier nuclei are not produced during BBN due to the absence of stable nuclei of mass numbers 5 and 8 and bigger Coulomb repulsion between them for charge numbers $Z > 1$. They can be made in stars (up to iron) or supernovae.

of light elements by modifying the expansion rate of the universe. The expansion rate is given by

$$H^2 = \frac{8\pi}{3} G\rho, \tag{5}$$

where G is Newton's constant, H the Hubble parameter and ρ the energy density of the universe. In the radiation-dominated era at the time of BBN, $\rho \simeq \rho_\gamma + \rho_\mathrm{e} + N_\nu \rho_\nu$, where the first two terms are the energy densities for photons and electrons/positrons and ρ_ν is the contribution from a flavour of neutrinos. N_ν is the *effective number of neutrino species*. In the standard scenario $N_\nu = 3$ during BBN[12], any deviation ΔN_ν from that can be used to parameterize a non-standard expansion rate. Despite the name, a $\Delta N_\nu \neq 0$ need not be caused by an additional neutrino species. It may, e.g., be due to any non-standard energy budget, gravitational waves, varying coupling constants or extra dimensions. A best fit to the observed element abundances with N_ν left as a free parameter, reported in [28], yields

$$\eta_{\mathrm{BBN}} = 6.07 \pm 0.33, \quad \Delta N_\nu = 0.62 \pm 0.46, \tag{6}$$

with ΔN_ν consistent with zero at $\sim 1.3\sigma$.[13] However, the precise values of these parameters are affected by the selection of datasets and estimates of systematic errors, cf the discussion in [27].

The main uncertainty results from the difficulty in measuring the primordial abundances of light elements. These differ from present-day values within galaxies, which have been modified by thermonuclear reactions in stars throughout the last 13 Gyears. N_ν is mainly sensitive to the ^{4}He abundance (because the expansion history determines the point of neutron freezeout, which affects the neutron fraction n/p in the plasma), and η is sensitive to D. In contrast to He, there are no known astrophysical sources of D [32]; thus the observed abundance provides a reliable lower bound on the primordial value. In fact, the BBN bounds on η are almost entirely derived from the D abundance. This has earned D the label 'baryometer' of the universe, and the strong dependence on D is the reason why η is relatively insensitive to the infamous ^{7}Li problem [29]. It is believed that the most precise measurement to date can be obtained from high-redshift low-metallicity quasar absorption systems, although the systematic errors are not fully understood, cf the discussion and references in [27].

3.2. Cosmic microwave background and large-scale structure

The baryon content of the universe can also be determined from the power spectrum of temperature fluctuations in the CMB. The temperature fluctuations were generated by acoustic oscillations of the baryon–photon plasma in the gravitational potential caused by small inhomogeneities in the dark matter (DM) distribution. The oscillations are sensitive to η because the baryon fraction determines the equation of state of the plasma, which mainly manifests in the relative height of odd and even peaks in the power spectrum. Since the decoupling of photons happens at a vastly different epoch ($T \sim 0.3\,\mathrm{eV}$) and the physics that produces the acoustic peaks in the power spectrum is very different from BBN, this is a truly independent measurement. The WMAP7 data [33] alone give, in units of 10^{-10},

$$\eta_{\mathrm{CMB}} = 6.160^{+0.153}_{-0.156}. \tag{7}$$

[12] At the time of CMB decoupling $N_\nu = 3.046$ in the SM, where the deviation from 3 parameterizes a deviation from the equilibrium distribution of neutrinos caused by $e^\pm$ annihilation [30].

[13] Recently, evidence from different sources that hints at $\Delta N_\nu > 0$ has mounted [31, 33], but the statistical significance does not allow a definite conclusion at this stage.

When the WMAP7 data are combined with large-scale structure (LSS) data [34] and the Hubble rate $H_0 = 74.2 \pm 3.6\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ found in [36], this value slightly changes to $\eta_{\mathrm{CMB/LSS}} = 6.176 \pm 0.148$ [33]. A similar analysis, combining different CMB and LSS datasets, was performed in [37] and gave results scattered between 6.1 and 6.16 for η in units of 10^{-10}. In the context of baryogenesis, $\mathcal{O}[1]$ corrections to the above numbers are of little relevance, given our lack of knowledge of physics beyond the SM. The impressive agreement between the BBN and the CMB results for η, however, is an important hint that we can reliably determine the magnitude of the BAU observationally.

3.3. A large lepton asymmetry?

The good agreement between the CMB and the BBN results strongly constrains the BAU to be as small as $\sim 10^{-10}$. Compared to that, bounds on a lepton asymmetry of the universe (LAU), hidden in the cosmic neutrino background (CNB), are much weaker. The only source of B-violation in the SM are sphaleron processes [13, 14], which are highly inefficient below $T_{\mathrm{EW}} \sim 140\,\mathrm{GeV}$, as would be suggested by a 126 GeV Higgs mass [35]. However, if neutrinos are Majorana particles, the Majorana mass term can lead to lepton number violating processes at much lower energies. Furthermore, neutrino mixing may add another source of CP-violation to the SM. Thus, it is possible to imagine non-equilibrium processes that generate an LAU below the electroweak scale that is orders of magnitude larger than the BAU. Although of little effect today, a large lepton asymmetry may have far-reaching consequence in the past. It can trigger a resonant production of DM, see section 4.3, or affect the nature of the quantum chromodynamics (QCD) transition [47].

The main constraints on the LAU come from BBN. It affects BBN in two ways. On the one hand, non-zero chemical potentials modify the momentum distribution of neutrinos. This changes the temperature dependence of the energy density and thereby the expansion history. More importantly, electron neutrinos ν_{e} participate in the conversion processes that keep neutrons and protons in equilibrium. The change in the freezeout value of n/p caused by a ν_{e} asymmetry leaves an imprint in the ^{4}He abundance.

The LAU has been studied by different authors [38–40]. It can be defined in analogy to (1),

$$\eta_\alpha = \left.\frac{N_{\nu_\alpha} - N_{\bar{\nu}_\alpha}}{N_\gamma}\right|_{T=3\,\mathrm{K}}. \tag{8}$$

In the absence of neutrino masses, there would be only weak constraints on $|\eta_\mu|, |\eta_\tau| \lesssim 2.6$ (in units of one!) [39] because at the time of BBN, electrons are the only charged leptons in the primordial plasma. η_{e} would be constrained to $-0.012 \lesssim \eta_{\mathrm{e}} \lesssim 0.005$ due to its effect on n/p. However, neutrino oscillations tend to make the lepton asymmetries in individual flavours equal[14] well before BBN [41–43] for values of the neutrino mixing angle θ_{13} suggested by experiment [44]. They tie the bounds for all flavours together and introduce a dependence on the choice of mass hierarchy and θ_{13}. For $\sin^2\theta_{13} = 0.04$, at the upper end of the region suggested in Fogli *et al* [48] and about twice the value found more recently in [45, 46, 49], the bounds found in [39] are $-0.17 \lesssim \eta_{e,\mu,\tau} \lesssim 0.1$ for normal hierarchy and $-0.1 \lesssim \eta_{e,\mu,\tau} \lesssim 0.05$

[14] This process is sometimes referred to as 'flavour equilibration', although the neutrino distribution functions may deviate from Fermi–Dirac because the process occurs close to the neutrino freezeout and neutrinos may not reach thermal equilibrium. This means that a lepton asymmetry cannot be translated into a chemical potential in the strict sense.

for inverted hierarchy. For inverted hierarchy, the dependence on θ_{13} is weak, while for normal hierarchy, values as large as $|\eta_{e,\mu,\tau}| \simeq 0.6$ are allowed for small θ_{13}. In [40], stronger bounds $-0.071 < \eta_{e,\mu,\tau} < 0.054$ were found for $\sin^2\theta_{13} = 0.04$, assuming normal hierarchy, and it was pointed out that future CMB observations may be able to compete with BBN in constraining η_α.

4. Testable theories of baryogenesis

4.1. Baryogenesis in the Standard Model (SM)

In principle, the Sakharov conditions (i)–(iii) are all fulfilled in the SM. This is rather obvious for conditions (ii) and (iii). The weak interaction violates P-invariance maximally, while CP-invariance is violated by the complex phase $\delta_{\rm KM}$ in the Cabibbo–Kobayashi–Maskawa matrix. The expansion of the universe brings the primordial plasma out of thermal equilibrium. The violation of baryon number, condition (i), occurs more subtly[15].

At the perturbative level, there are four conserved fermion numbers in the SM: the baryon number B and three lepton numbers L_α. The observed neutrino oscillations, which cannot be explained within the SM, clearly violate the individual lepton numbers L_α. If neutrinos are Majorana particles (such as, e.g., in the model presented in section 4.3), the Majorana mass term also violates the total lepton number $L = \sum_\alpha L_\alpha$. The baryon number B is conserved at each order in perturbation theory, but violated by non-perturbative effects [14]. This can be seen by looking at the baryonic current j^B_μ. Note that j^B_μ is conserved classically, but obtains a non-zero divergence by a quantum anomaly [52],

$$\partial^\mu j^B_\mu = \frac{n_{\rm f}}{32\pi^2}(-g^2\,{\rm tr}(F_{\mu\nu}\tilde{F}^{\mu\nu}) + g'^2 F'_{\mu\nu}\tilde{F}'^{\mu\nu}), \tag{9}$$

where g, $F_{\mu\nu}$ and g', $F'_{\mu\nu}$ are the gauge coupling and field strength tensor of the SU(2) and $U(1)$ gauge interactions, respectively, and $n_{\rm f} = 3$ is the number of fermion families. Baryon number violation is most easily explained semi-classically by *fermionic level crossing* [53, 54]. In the bosonic sector of the standard electroweak theory, there is an infinite number of field configurations that minimize the static energy functional, which we refer to as 'vacua'. They are physically equivalent, but can be distinguished by the Chern–Simons number $N_{\rm CS}$ of the gauge field configuration. The energy levels of fermions depend on the bosonic background fields. Fermionic level crossing occurs when $N_{\rm CS}$ changes; then an energy level raises above (or falls below) the surface of the Dirac sea, see figure 1, which means that fermions are created (or absorbed) by the background. All SU(2) doublets are the subject of level crossing, leading to the simultaneous creation (or disappearance) of nine quarks and three leptons. Thus, $L_\alpha - \frac{B}{3}$ remain conserved in sphaleron processes although B and L_α are violated individually. The different vacua are separated by a potential barrier the height of which can be estimated by the *sphaleron* energy $M_{\rm sph} \sim M_W/\alpha_W$. The sphaleron is the field configuration of maximal energy along the path of minimal energy in field space that connects two minima in the classical potential [55].

In quantum field theory, the early universe can be described as a thermodynamic ensemble characterized by a density matrix $\hat{\varrho} = \exp(-\hat{H}/T)$, where $\hat{H}$ is the Hamiltonian. At low temperatures $T \ll T_{\rm EW}$, only configurations with field expectation values near the minima of the effective potential are significantly populated. Tunneling through the potential barrier is the only process that can change $N_{\rm CS}$ from such an initial state. The tunneling rate at $T = 0$ [14] is suppressed by $\exp(-\frac{4\pi}{\alpha_W}) \sim 10^{-160}$, effectively forbidding B-violation in vacuum.

[15] See [50] for a pedagogical discussion.

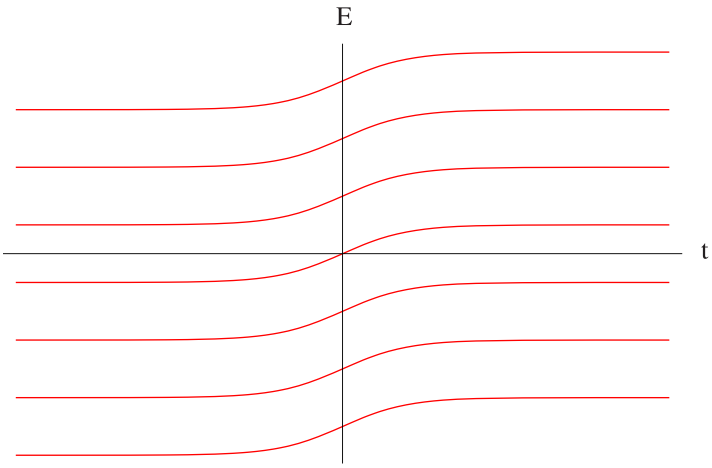

Figure 1. An illustration of fermionic level crossing: the changing bosonic background fields can modify the fermionic energy levels, leading to fermion number violation when a level raises above the surface of the Dirac sea.

Near $T \sim T_{\rm EW}$ the Boltzmann suppression $\exp(-\hat{H}/T)$ is less efficient and $N_{\rm CS}$ can change by a classical transition due to thermal fluctuations. The probability for these baryon number violating processes is governed by the sphaleron rate [51]

$$\Gamma_{\rm sph} \equiv \lim_{t,V\to\infty} \frac{(N_{\rm CS}(t) - N_{\rm CS}(0))^2}{Vt} = \int {\rm d}^4x \langle \partial^\mu j^B_\mu(x) \partial^\nu j^B_\nu(0)\rangle, \tag{10}$$

where V is the total volume. The (finite-temperature) effective potential and sphaleron configuration change in the vicinity of the electroweak symmetry restoration. In the Higgs phase, $\Gamma_{\rm sph}$ is given by

$$\Gamma_{\rm sph} = A\ (\alpha_W T)^4 \left(\frac{M_{\rm sph}}{T}\right)^7 \exp\left(-\frac{M_{\rm sph}}{T}\right) \quad \text{(Higgs phase)}, \tag{11}$$

where A is a coefficient that can be determined numerically [59–70]. For $T \gg T_{\rm EW}$, in the symmetric phase, the Boltzmann suppression is cancelled because M_W in $M_{\rm sph}$ is replaced by the non-abelian magnetic screening scale $\sim\alpha^2 T$, and $\Gamma_{\rm sph}$ reads as [56] (see also [58])

$$\Gamma_{\rm sph} = (25.4 \pm 2.0)\alpha_W^5\, T^4 \quad \text{(symmetric phase)} \tag{12}$$

with $\alpha_W = g^2/4\pi$. A more refined expression for the general SU(N) can be found in [57]. For Higgs masses between 100 and 300 GeV, sphaleron reactions in the SM become slower than the rate of the universe's expansion at a temperature $T_{\rm sph}$, with $100 \lesssim T_{\rm sph} \lesssim 300\,\text{GeV}$ [71]. Above this temperature, the baryon number is efficiently violated and all Sakharov conditions are fulfilled. Thus, the SM, in principle, can provide a framework for baryogenesis.

However, it turns out that both, the violation of CP, condition (ii), and the deviation from thermal equilibrium, condition (iii), are not large enough to produce the observed η (and thus Ω_B). The amount of CP-violation can be estimated by constructing reparametrization invariant objects out of the quark mass matrices [72, 73]. The lowest order CP-non-invariant combination is the Jarlskog determinant [74], which in terms of quark masses and mixing angles reads as

$$D = \sin(\theta_{12})\sin(\theta_{23})\sin(\theta_{13})\delta_{\rm KM}(m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2). \tag{13}$$

A dimensionless quantity can be constructed when dividing by the relevant temperature T_{sph}, at which the BAU freezes out, to the 12th power, $D/T_{sph}^{12} \sim 10^{-20} \ll \eta$. Although not a direct proof of impossibility, the smallness of this result makes baryogenesis within the SM very challenging [72, 73, 75–77].

During most of the history of the universe, cosmic expansion is the only source of non-equilibrium. Within the SM, the BAU has to be created around $T \sim T_{sph}$, as otherwise it would be washed out by sphaleron processes. At these temperatures, all particle reactions in the SM act much faster than cosmic expansion (their rates are much higher than the Hubble parameter), keeping all particle species very close to thermal equilibrium. The only way to cause a significant deviation from equilibrium at $T \sim T_{sph}$, necessary to satisfy condition (iii) [79], would be a first-order phase transition from the symmetric to the Higgs phase of the electroweak theory [75]. It proceeds via nucleation of bubbles of new (Higgs) phase. The bubbles expand rapidly, as the field configuration inside is energetically more favourable. The mechanism of baryogenesis related to bubble wall expansion is based on the following picture [80] (for the spinodial decomposition phase transition, see [81]). When the bubble wall, which separates the symmetric phase from the Higgs phase, passes through the medium, it can cause a large deviation from equilibrium. Due to the CP-violation, the reflection and transmission coefficients for quarks and antiquarks colliding with the bubble wall are different; this allows for the generation of a matter–antimatter asymmetry, which can dissipate into the bubble. It is preserved in the Higgs phase from washout because sphalerons are inefficient, but disappears in the symmetric phase, where baryon number non-conservation is rapid.

In the electroweak theory the symmetric and the Higgs phases are continuously connected. A first-order phase transition could only occur if the Higgs mass were below 72 GeV [82–84]; this is in clear contradiction with experimental data [35], allowing us to conclude that it is extremely unlikely that the observed BAU can be generated within the SM.

Over the last decade, two clear signs of particle physics beyond the SM other than the BAU have been found experimentally. These are the discovery of neutrino flavour changing processes, usually interpreted as oscillations (for a comprehensive review and references to original experimental and theoretical work see [78]) and the conclusion that the observed DM cannot be baryonic. The latter is based on BBN and CMB precision data [27, 33], which in combination with accurate measurements of the Hubble parameter [36] and simulations of structure formation show that the amount of matter in the universe exceeds the amount of baryonic matter by a factor of $\sim$6 [23]. The explanation of these experimental facts unavoidably requires physics beyond the SM. Extensions of the SM generally contain new sources of CP violation and often also B violation, and there is not much motivation to insist on a source for the BAU within the SM. In section 4.3 we explore the possibility that neutrino oscillations and the observed DM have a common origin that is also responsible for the BAU.

4.2. Beyond the SM

Baryogenesis necessarily involves B-violating processes due to condition (i). At the same time, the current non-observation of these, e.g. in proton decay or n–$\bar{n}$-oscillations, strongly constrains B-violation in the present-day universe. A large number of models that are in accord with these conditions have been suggested since Sakharov. Often they are grouped into those that directly generate a matter–antimatter asymmetry in the baryonic sector and those that initially generate a lepton asymmetry (‘leptogenesis’), which is then transferred to the baryonic sector, either by SM sphalerons or processes that involve physics beyond the SM.

One can alternatively classify the variety of models into *top-down* and *bottom-up* approaches. In top-down approaches, the underlying theory has usually not been developed for the purpose of explaining the BAU, but is motivated by more general theoretical or aesthetic considerations. The most prominent examples are grand unifying theories (GUT) and supersymmetry, but also string inspired scenarios. The requirement to predict the correct BAU is a necessary condition that can be used to constrain the parameter space for these classes of models.

Bottom-up approaches, on the other hand, take the SM as a basis and add ingredients that allow us to explain the BAU. Ideally, these account also for other phenomena that cannot be explained within the SM. A guideline for the exploration of the infinite-dimensional space of possible SM extensions can be the principle of minimality ('Ockhams razor'), often accompanied by 'naturalness' considerations. We discuss a specific model that obeys these principles in section 4.3. Bottom-up models may be viewed as effective field theories, without knowledge of the underlying physics at higher energy scales.

Although theoretically very interesting, most models of baryogenesis are hard to falsify. They may remain viable even if no signals are observed in any experiments in the centuries to come, as they can be saved from falsification by pushing up an associated energy scale. In some cases, indirect evidence that supports the underlying theory may be found in low-energy experiments or astrophysical observations, but even then it would be unlikely that these data single out one model and the source of the BAU can be identified uniquely. In the foreseeable time, only three of the popular scenarios are testable in the strict sense that all parameters of the theory may be measured: electroweak baryogenesis, resonant leptogenesis [86] and baryogenesis from sterile neutrino oscillations [87, 90]. The former two are covered in other parts [85] in this focus issue; we therefore in the following only discuss baryogenesis from neutrino oscillations.

4.3. Baryogenesis from sterile neutrino oscillations

In the SM, neutrinos are the only fermions that appear only as left chiral fields. At the same time, neutrino flavour changing processes, usually interpreted as oscillations, cannot be explained within the model. Complementing the SM by right-handed neutrinos, singlet under all gauge interactions, offers an attractive explanation for neutrino oscillations due to masses generated by the seesaw mechanism [89]. This model is described by the Lagrangian

$$\mathcal{L}_{\nu\mathrm{MSM}} = \mathcal{L}_{\mathrm{SM}} + \mathrm{i}\bar{\nu_{\mathrm{R}}}\,\partial\!\!\!/\,\nu_{\mathrm{R}} - \bar{L_{\mathrm{L}}} F \nu_{\mathrm{R}} \tilde{\Phi} - \bar{\nu_{\mathrm{R}}} F^{\dagger} L_{\mathrm{L}} \tilde{\Phi}^{\dagger} - \tfrac{1}{2}(\bar{\nu_{\mathrm{R}}^{c}} M_{\mathrm{M}} \nu_{\mathrm{R}} + \bar{\nu_{\mathrm{R}}} M_{\mathrm{M}}^{\dagger} \nu_{\mathrm{R}}^{c}), \tag{14}$$

where we have suppressed flavour and isospin indices. $\mathcal{L}_{\mathrm{SM}}$ is the Lagrangian of the SM. F is a matrix of Yukawa couplings and M_{M} a Majorana mass term for the right-handed neutrinos ν_{R}. $L_{\mathrm{L}} = (\nu_{\mathrm{L}}, e_{\mathrm{L}})^{\mathrm{T}}$ are the left-handed lepton doublets and Φ is the Higgs doublet in the SM.

The Lagrangian (14), with eigenvalues of M_{M} far above the electroweak scale, is the basis of thermal leptogenesis scenarios [88], in which the CP-asymmetry responsible for the BAU is generated during the freeze-out and decay of right-handed neutrinos. An attractive feature of this setup is that it provides a common explanation for the small neutrino masses and the BAU within GUTs.

For eigenvalues of M_{M} below the electroweak scale, the Lagrangian (14) yields the possibility that the asymmetry was created during the thermal production of right-handed (sterile) neutrinos in the early universe—rather than during their freezeout and decays [87, 90].

This mechanism was called baryogenesis via (sterile) neutrino oscillations in [87]. It is, however, also efficient when the oscillations are practically not relevant because they are, e.g., too rapid and average out. The crucial point is that the initial sterile neutrino abundance deviates from its equilibrium value, and chemical equilibrium is not established before sphaleron freeze-out.

This possibility is realized in the *neutrino minimal Standard Model* (νMSM), which can be viewed as a minimal extension of the SM. This, in particular, means that there is no modification of the gauge group, the number of fermion families remains unchanged and no new energy scale above the Fermi scale is introduced. It can explain simultaneously three empirical facts that cannot be understood within the framework of the SM: the observed neutrino oscillations, dark matter and the BAU. Here we focus on the latter. An introduction to the νMSM, along with the most recent bounds on its parameter space, can be found in [95]; for further reading see [90–94, 97, 100].

The Lagrangian (14) yields six different neutrino mass eigenstates. Three of them are mixes of the 'active' SM neutrinos ν_α ($\alpha = e, \mu, \tau$) with masses m_i. The other three are 'sterile' neutrinos N_1, N_2 and N_3 with masses M_I. Mixing between active and sterile neutrinos is suppressed by small angles $\theta_{\alpha I} = (m_{\rm D} M_{\rm M}^{-1})_{\alpha I}$, where $m_{\rm D} = Fv$ and v is the Higgs expectation value. The mass matrix m_ν for the active neutrinos, leading to the observed neutrino oscillations, is generated by the seesaw mechanism [88, 89]; $m_\nu \simeq -\theta M_{\rm M} \theta^{\rm T}$. For eigenvalues of $M_{\rm M}$ below the electroweak scale, this requires the Yukava couplings F to be tiny.

The requirement to produce the correct BAU can be used to constrain the νMSM parameter space and find the experimentally interesting region. In the following, we assume that only two sterile neutrinos $N_{2,3}$ participate in baryogenesis, which leaves open the possibility to use N_1 as DM candidate. In the simplest scenario, $N_{2,3}$ are not produced during reheating due to their tiny Yukawa interactions [98]. Instead, they are produced thermally from the primordial plasma during the radiation-dominated epoch. Since they are generated as flavour eigenstates, they undergo oscillations. Throughout this non-equilibrium process, all Sakharov conditions are fulfilled and baryogenesis is possible if several requirements are fulfilled. On the one hand, the (temperature-dependent) mass splitting $|\delta M| = |M_3 - M_2|/2$ has to be large enough for the neutrinos to perform several oscillations; on the other hand it has to be small to ensure resonant amplification. Finally, $N_{2,3}$ should not reach chemical equilibrium before sphaleron freezeout to avoid washout.

If the νMSM shall, apart from the BAU, also explain the observed DM density $\Omega_{\rm DM}$, the lightest sterile neutrino (N_1) is required to be sufficiently long lived to constitute all DM. Then its mixing angle is too small to be seen in collider experiments. However, being a decaying DM candidate, it can be searched for indirectly by astronomical observations [97]. These, together with the seesaw formula, constrain the N_1 mass to $1\,{\rm keV} \lesssim M_1 \lesssim 50\,{\rm keV}$. This implies that one active neutrino is effectively massless, which fixes the absolute scale of neutrino masses. In contrast, $N_{2,3}$ can be seen directly at collider experiments [99]. Another consequence of the small N_1 mixing is that its coupling is too small to contribute to the generation of a BAU. Baryogenesis can therefore be described in an effective theory with only two sterile neutrinos $N_{2,3}$. CP-violating oscillations among them can generate a lepton asymmetry, which can be translated into a BAU by SM sphalerons. It turns out that for $N_{2,3}$ masses $M_{2,3} = \bar{M} \mp \delta M$ in the GeV range, which are accessible to direct search experiments, the observed BAU can only be generated when the masses are quasi-degenerate, i.e. $\delta M \ll \bar{M}$. The degeneracy is essential for a resonant amplification of the CP-violating effects. If one, however, drops the requirement that the Lagrangian (14) shall also explain the observed DM, all three sterile neutrinos can participate in baryogenesis. It has been found in [96] that in this case, no mass degeneracy is needed due to the additional sources of CP-violation in the couplings of N_1.

The parameter space can be studied in a quantitative manner by means of effective kinetic equations, similar to those commonly used in neutrino physics [93, 107]. They allow us to track the time evolution of the N_I and lepton chemical potentials. Detailed studies have been performed in [94, 95, 100]. During this calculation one can approximate $M_1 = 0$ and drop N_1 from the Lagrangian, which has no effect on baryogenesis. This leaves 11 parameters in addition to the SM. In the Casas–Ibarra parametrization for F [101], these are: three active mixing angles, two active neutrino masses, two Majorana masses $M \pm \Delta M$ in M_{M}, one Dirac phase, one Majorana phase and the real and imaginary parts of a complex angle ω.

Figure 2 shows the sterile neutrino masses $\bar{M} \simeq M$ and mixings $U^2 = \mathrm{tr}(\theta^\dagger \theta)$ for which the observed BAU can be generated by the two sterile neutrinos $N_{2,3}$. It also displays other experimental bounds and constraints from BBN. To obtain these results, all known parameters have been fixed to their experimental values found in [48], while the CP-violating phases have been chosen to maximize the lepton asymmetries.

If one requires the N_1 density to make up for the observed Ω_{DM}, its thermal production rate needs to be amplified resonantly [102]. The resonant amplification is due to a level crossing between active and sterile neutrino dispersion relations, caused by the MSW effect [108, 109], and requires the presence of a lepton asymmetry $|N_L - N_{\bar{L}}|/s \gtrsim 8 \times 10^{-6}$ in the plasma [103]. This LAU, which exceeds the BAU by orders of magnitude, has to be produced during the freezeout and decay of $N_{2,3}$. Such a large asymmetry can only be generated from $N_{2,3}$ oscillations if their masses are highly degenerate, with a physical mass splitting δM of the order of active neutrino masses m_i [94]. This degeneracy is much stronger than that required to explain the BAU. Thus, the BAU and DM production in the νMSM are both related to lepton asymmetries in the early universe, produced by the same sources of CP-violation. This may give a clue to understand the similarity $\Omega_{\mathrm{DM}} \sim \Omega_B$, although it does not provide an obvious explanation because today's values of Ω_B and Ω_{DM} depend on several other parameters. The need to generate a sufficient LAU allows us to impose further constraints on the sterile neutrino properties. This was included in the analysis in [94, 95]. The computational effort needed for quantitative studies is huge, as it requires us to track time evolution from hot big bang initial conditions down to temperatures $\sim$100 MeV, below hadronization. At different temperatures, different processes enter the effective Hamiltonian. Various time scales, related to production, oscillations, decoherence, freeze-out and decay of the N_I are involved. A detailed study has been performed in [94, 95].

Currently, the main uncertainty in these results comes from the kinetic equations. The BAU is generated from a quantum interference, in a regime where coherent oscillations can be essential. The semiclassical kinetic equations known from neutrino physics most likely capture the main features of this process, but may require corrections in the resonant regime. A first-principles derivation [116, 118] is required to determine the size of these. This is not entirely specific to the νMSM; a consistent description of transport phenomena involving quantum interference, flavour effects and CP-violation remains an active field of research in many scenarios of baryogenesis [110–124].

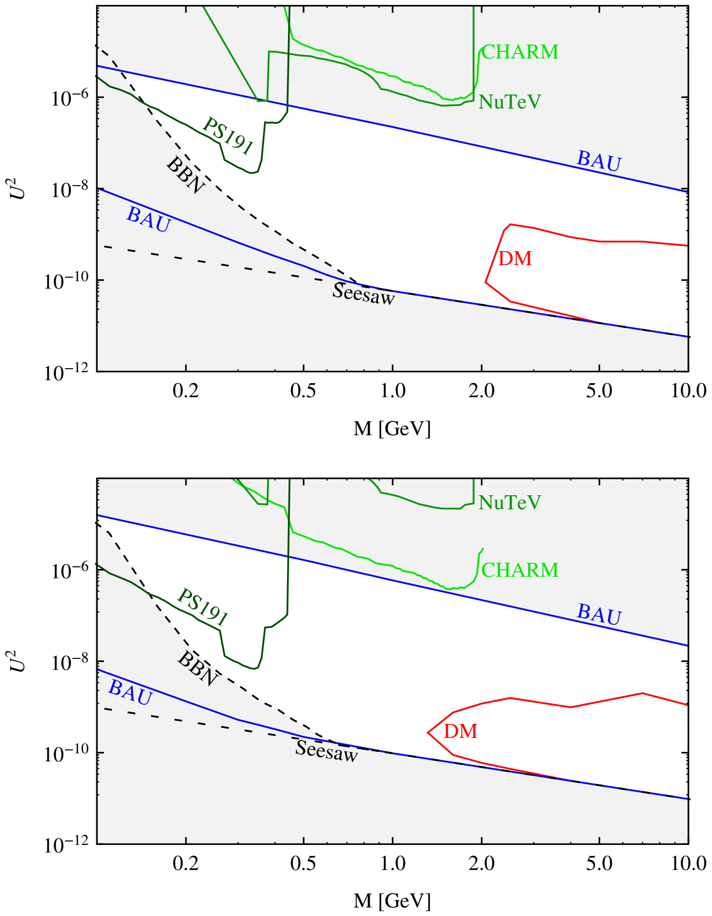

Figure 2. Constraints on the sterile neutrino mass M and mixing $U^2 = \mathrm{tr}(\theta^\dagger\theta)$ in the νMSM as found in [94, 95] for normal (upper panel) and inverted (lower panel) hierarchy of active neutrino masses. In the regions below the black dashed 'seesaw' line there exists no choice of νMSM parameters that is in accordance with experimental constraints on the active neutrino mixing matrix. In the region below the black dotted BBN line, the lifetime of $N_{2,3}$ particles in the early universe is larger than 0.1 s, leading to the danger that their decay spoils the agreement between BBN calculations and the observed light element abundances. The regions above the green lines of different shades are excluded by the NuTeV [104], CHARM [105] and CERN PS191 [106] experiments, as indicated in the plot. In the region between the blue lines, a CP-asymmetry that explains the observed BAU can be produced during the thermal production of $N_{2,3}$. In the region within the red line, thermal production of N_1 (resonant and non-resonant) is sufficient to explain all the observed DM. The CP-violating phases that maximize the efficiency of baryogenesis and DM production are different. They were chosen independently for the blue and red lines displayed here. The region in which Ω_B and Ω_{DM} can be explained *simultaneously* almost coincides with the area inside the red line, see [95].

5. Conclusions

The origin of matter remains one of the great mysteries in physics. Observationally, we can be almost certain that the present-day universe contains no significant amounts of (baryonic) antimatter, and the baryons are the remnant of a small matter–antimatter asymmetry $\sim 10^{-10}$ in the early universe. This asymmetry cannot be explained within the SM of particle physics and cosmology. It provides, in addition to neutrino oscillations, dark matter and accelerated cosmic expansion, one of the few observational proofs of physics beyond the SM. Many extensions of the SM are able to explain the BAU. However, since it is characterized by only one observable number, the BAU cannot be used to pin down the correct model realized in nature. In spite of that, it provides a necessary condition that can be used to exclude or constrain models, and baryogenesis remains a very active field of research. Among the many suggested theories of baryogenesis, only a few are experimentally testable. We discussed an example of this kind, in which right-handed neutrinos are the common origin of the BAU, DM and neutrino oscillations.

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