A Weak-Isospin-Based Resolution of Particle–Antiparticle and Baryon Asymmetry Problems

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Abstract

This study begins with the recognition that the Standard Model particle–antiparticle classification lacks a universal physical principle that determines the particle orientation of each charge-conjugate pair while grouping the proton, neutron, and electron into the same particle sector. Motivated by the weak-isospin doublet structure of weak fermion transitions, we introduce a new weak-isospin-based quantum number, $N = 2T_{3L}$, where T_{3L} is the third component of left-handed weak isospin. States with $N > 0$ are assigned to the particle sector, states with $N < 0$ to the antiparticle sector, and states with $N = 0$ to an N-neutral sector. In this classification, the proton and neutrino are particles, whereas the electron and neutron are antiparticles. The representative weak, hadronic, stellar, and early-Universe processes examined here consistently preserve the total additive N balance while redistributing N among different species. For fermion species defined by their left-handed weak-doublet orientation, the electroweak charge assignments give $N = 2Q - (B - L)$, where Q, B, and L denote electric charge, baryon number, and lepton number. Hence, for charge-conserving processes, exact additive N conservation requires $\Delta(B - L) = 0$. Accordingly, the same Universe that appears strongly particle–antiparticle asymmetric under the conventional classification is reinterpreted in the weak-isospin-based classification as a Universe in which positive-N and negative-N components cancel globally, yielding the global N-symmetry condition $N_{\text{tot}} = 0$. This work further proposes a possible particle physics mechanism for the species-level particle–antiparticle and baryon asymmetry problems. A proposed N-conserving $1 \to 3$ decay process such as $\bar{n} \to p + e^- + \nu_e$ can generate, in a single decay event, the asymmetry direction required to account for the present cosmic particle abundance pattern, $(\delta\Delta_p, \delta\Delta_n, \delta\Delta_e, \delta\Delta_\nu) = (+1, +1, +1, +1)$. Related $2 \to 2$ scattering processes such as $\bar{n} + e^+ \to p + \nu_e$ and $\bar{n} + \bar{\nu}_e \to p + e^-$ produce the same asymmetry direction. Accordingly, this work recovers global particle–antiparticle symmetry through the $N = 2T_{3L}$ classification and proposes a possible solution to the species-level particle–antiparticle asymmetry through new N-conserving particle-conversion processes. The proposed mechanism can be tested directly through searches for N-conserving $1 \to 3$ decay and $2 \to 2$ scattering channels and their CP-conjugate rate asymmetries, while cosmic neutrino asymmetry, $B - L$ violation, and the nature of neutrinos provide additional tests of the broader framework.

Contents

1 Introduction

1.1 The Matter–Antimatter Asymmetry of the Universe and Existing Approaches

One of the most fundamental problems in modern cosmology and particle physics is the matter–antimatter asymmetry of the Universe. In the high-temperature environment of the early Universe, thermal processes produced and annihilated particle–antiparticle pairs, while relativistic quantum field theory describes particles together with their corresponding antiparticle states. Nevertheless, the ordinary matter observed in the Universe today is overwhelmingly matter rather than antimatter and is composed primarily of protons, neutrons, and electrons, whereas antimatter such as antiprotons, antineutrons, and positrons is extremely rare as a macroscopic component of the Universe [1].

In the conventional classification of the Standard Model, protons and neutrons are both classified as baryons, whereas antiprotons and antineutrons are classified as antibaryons. Accordingly, the observed dominance of baryons over antibaryons in the present Universe is formulated more specifically as the baryon asymmetry of the Universe (BAU). To explain this asymmetry, baryogenesis and leptogenesis mechanisms have been extensively investigated [1, 2]. The classic Sakharov conditions require baryon-number violation, C- and CP-symmetry violation, and departure from thermal equilibrium for dynamical generation of a baryon asymmetry from an initially symmetric state [3].

Before introducing mechanisms that generate such an asymmetry, however, this study raises a more fundamental question:

$$\boxed{\text{Is the particle–antiparticle classification currently in use itself physically correct?}} \quad (1)$$

In other words, this study reexamines whether treating the protons, neutrons, and electrons that constitute ordinary cosmic matter as states on the same matter (or particle) side of the conventional particle–antiparticle classification reflects a more fundamental symmetry of nature.

1.2 Historical Formation of the Particle–Antiparticle Concept and Incompleteness of the Conventional Classification

The modern particle–antiparticle concept developed from Dirac's relativistic theory of the electron and the subsequent antiparticle interpretation of its negative-energy solutions [4, 5]. Anderson's observation of the positive electron then provided direct experimental evidence for the positron [6]. Relativistic quantum field theory subsequently established particle and antiparticle states as corresponding charge-conjugate excitations of quantum fields [7].

Quantum field theory provides a well-defined relation between a state and its charge-conjugate partner [7]. However, this relation by itself does not provide a universal physical principle that determines which member of each charge-conjugate pair must be assigned to the particle sector across different fermion species. In particular, the charge-conjugation relations $p \longleftrightarrow \bar{p}$, $n \longleftrightarrow \bar{n}$, and $e^- \longleftrightarrow e^+$ remain mathematically intact even if the particle–antiparticle orientation assigned to one pair is reversed relative to another [7]. The existence of a charge-conjugate pairing therefore does not, by itself, determine that p, n, and e^- must all be assigned to the same particle-species sector. The question addressed in this work is precisely whether a universal physical criterion exists for determining this cross-species particle–antiparticle orientation.

Consequently, which member of a charge-conjugate pair is designated as the particle and which as the antiparticle has not been determined by a universal physical principle. Moreover, there is no established physical basis for concluding that the present particle–antiparticle nomenclature necessarily coincides with a more fundamental symmetry structure of nature.

Motivated by the incompleteness of the conventional particle–antiparticle classification, this study investigates whether the weak interaction provides a universal physical criterion for determining particle–antiparticle orientation. Weak interactions govern fermion transitions such as beta decay and flavor-changing weak decays, and the electroweak gauge structure underlying these processes was established through the works of Glashow, Weinberg, and Salam [8–10]. In the Standard Model, left-handed quarks and leptons form weak-isospin doublets in each generation [1,7].

For the first generation,

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \qquad \begin{pmatrix} \nu_{eL} \\ e_L^- \end{pmatrix}, \tag{2}$$

the upper and lower components carry opposite values of the third component of weak isospin,

$$T_{3L} = +\frac{1}{2} \qquad \text{and} \qquad T_{3L} = -\frac{1}{2}, \tag{3}$$

respectively. The same weak-isospin structure is repeated in the second and third fermion generations [1].

The weak-isospin doublet structure is directly connected to the gauge structure that governs charged-current fermion transitions. Motivated by this physical structure, the present study examines whether particle–antiparticle orientation can instead be classified according to weak-isospin orientation.

1.3 Purpose of This Study: A New Particle–Antiparticle Classification and the Recovery of Global Particle–Antiparticle Symmetry

The purpose of this study is to introduce a new signed quantum number N, based on weak-isospin orientation, and to use it to reexamine the conventional particle–antiparticle classification. The explicit definition of N and its application to fermions, composite hadrons, baryons, and leptons are presented in the following section.

This study examines whether the weak-isospin-based classification remains consistent across the three generations of fermions, composite hadrons, weak decays, and gauge interactions, and extends the analysis to macroscopic processes including stellar fusion and proton–neutron conversion in the early Universe. It also investigates how the new classification changes the interpretation of the observed matter–antimatter and baryon asymmetries.

The central hypothesis of this study is that the conventional interpretation of the observed species-level abundance differences as a fundamental global particle–antiparticle asymmetry may depend on the particle–antiparticle classification used across different fermion species. If the new classification and its associated N-symmetry are maintained across microscopic interactions and cosmological evolution, the present Universe may be reinterpreted not as an asymmetric Universe in which particles have survived almost exclusively, but as a Universe in which particles and antiparticles maintain a global particle–antiparticle symmetry.

In addition, this study proposes N-conserving particle-conversion processes, including $1 \to 3$ decays (e.g., $\bar{n} \to p + e^- + \nu_e$) and related $2 \to 2$ scattering processes, as a possible particle physics mechanism for the remaining species-level particle–antiparticle asymmetry problem. The representative N-conserving process family considered here can simultaneously shift the proton, neutron, electron, and neutrino species asymmetries in the same direction. Their possible microscopic and cosmological roles are considered in Sec. 6.3.

2 Weak-Isospin-Based Particle–Antiparticle Classification

2.1 Weak-Isospin Orientation and the New Quantum Number N

In the Standard Model, left-handed quark and lepton fields form weak-isospin doublets in each generation [1, 7].

The three generations of quarks are arranged as

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \qquad \begin{pmatrix} c_L \\ s_L \end{pmatrix}, \qquad \begin{pmatrix} t_L \\ b_L \end{pmatrix}, \tag{4}$$

while the three generations of leptons are arranged as

$$\begin{pmatrix} \nu_{eL} \\ e^-_L \end{pmatrix}, \qquad \begin{pmatrix} \nu_{\mu L} \\ \mu^-_L \end{pmatrix}, \qquad \begin{pmatrix} \nu_{\tau L} \\ \tau^-_L \end{pmatrix}. \tag{5}$$

Within each weak-isospin doublet, the upper component has

$$T_{3L} = +\frac{1}{2}, \tag{6}$$

whereas the lower component has

$$T_{3L} = -\frac{1}{2}. \tag{7}$$

These weak-isospin assignments are part of the electroweak structure of the Standard Model [1, 7]. The present work adopts this established doublet orientation as the physical basis for distinguishing particles from antiparticles.

For each fermion species f defined by its left-handed weak-doublet orientation, we define a new signed species-level classification quantum number from the third component of weak isospin of its left-handed field,

$$\boxed{N_f \equiv 2T_{3L}(f_L)}. \tag{8}$$

Accordingly, a fermion species whose left-handed component occupies the upper component of a weak-isospin doublet has

$$N = +1, \tag{9}$$

whereas a fermion species whose left-handed component occupies the lower component has

$$N = -1. \tag{10}$$

We then define the new particle–antiparticle classification by

$$\boxed{N > 0: \text{ particle sector}, \qquad N < 0: \text{ antiparticle sector}, \qquad N = 0: \ N\text{-neutral sector}}. \tag{11}$$

Accordingly, the present classification is not strictly binary, but contains a third N-neutral sector in addition to the particle and antiparticle sectors.

States in the $N = 0$ sector are not necessarily self-conjugate. However, any genuinely self-conjugate state must carry $N = 0$ if the charge-conjugation rule $N(\bar{X}) = -N(X)$ is maintained.

It is useful to distinguish three logically different levels of the present framework from the outset.

First, the weak-isospin-based species-level classification is defined by

$$\boxed{N_f = 2T_{3L}(f_L)}. \tag{12}$$

This relation assigns an N value to each fermion species defined by its left-handed weak-doublet orientation and determines its particle–antiparticle orientation according to the sign of N. By itself, this classification does not require N to be an exactly conserved additive quantity.

Second, the stronger exact additive-N conservation hypothesis requires

$$\boxed{\Delta N = 0} \tag{13}$$

for every allowed physical process within the domain in which the additive N assignment is applied. This condition requires the total N to be conserved, but does not by itself require its value to vanish.

Third, the global N-symmetry condition is

$$\boxed{N_{\text{tot}} = 0}. \tag{14}$$

This is a global state condition rather than a consequence of additive conservation alone. If exact additive N conservation holds and $N_{\text{tot}} = 0$ is realized initially, the global zero-N condition is subsequently preserved.

Thus, the three statements

$$N_f = 2T_{3L}(f_L), \qquad \Delta N = 0, \qquad N_{\text{tot}} = 0 \tag{15}$$

represent, respectively, the species-level classification, exact additive N conservation, and global N symmetry. They should therefore be distinguished throughout the following analysis.

Under the weak-isospin-based species-level classification,

$$u, \ c, \ t, \ \nu_e, \ \nu_\mu, \ \nu_\tau \tag{16}$$

belong to the particle sector, whereas

$$d,\ s,\ b,\ e^-,\ \mu^-,\ \tau^- \tag{17}$$

belong to the antiparticle sector.

A central feature of this construction is that the definition of N does not contain the electric charge Q, the conventional baryon number B, or the conventional lepton number L. The weak-isospin orientation of the fermion doublet directly determines the particle–antiparticle orientation.

For clarity, Table 1 summarizes the basic fermion groups in the new weak-isospin-based classification.

Table 1: Basic fermion groups in the new weak-isospin-based particle–antiparticle classification.

Basic fermion group	**Members**	N	**New classification**
Up-type quarks	$u,\ c,\ t$	+1	Particle
Neutrinos	$\nu_e,\ \nu_\mu,\ \nu_\tau$	+1	Particle
Down-type quarks	$d,\ s,\ b$	−1	Antiparticle
Charged leptons	$e^-,\ \mu^-,\ \tau^-$	−1	Antiparticle

An immediate consequence is that the neutrino and the charged lepton do not possess the same particle orientation merely because they belong to the same lepton family. The neutrino occupies the upper component of the weak-isospin doublet, whereas the charged lepton occupies the lower component. Therefore,

$$\boxed{N(\nu) = +1, \qquad N(e^-) = -1}. \tag{18}$$

Likewise, the up-type and down-type quarks possess opposite N orientations,

$$\boxed{N(u,c,t) = +1, \qquad N(d,s,b) = -1}. \tag{19}$$

Thus, in the present classification, the weak-isospin doublet itself provides the fundamental orientation structure that distinguishes the particle and antiparticle sectors.

2.2 Charge Conjugation and Reversal of the N Orientation

We extend the N assignment to charge-conjugate states by requiring

$$N(\bar{f}) = -N(f). \tag{20}$$

If a fermion f has

$$N(f) = N_f, \tag{21}$$

its charge-conjugate state has

$$N(\bar{f}) = -N_f. \tag{22}$$

For example,

$$N(e^-) = -1, \qquad N(e^+) = +1, \tag{23}$$

while

$$N(\nu) = +1, \qquad N(\bar{\nu}) = -1. \tag{24}$$

Therefore,

$$\boxed{e^- : \text{ antiparticle}, \qquad e^+ : \text{ particle}}, \tag{25}$$

and

$$\boxed{\nu : \text{ particle}, \qquad \bar{\nu} : \text{ antiparticle}}. \tag{26}$$

The same rule applies to the quark sector,

$$N(u) = +1 \quad \Longrightarrow \quad N(\bar{u}) = -1, \tag{27}$$

and

$$N(d) = -1 \quad \Longrightarrow \quad N(\bar{d}) = +1. \tag{28}$$

Hence every charge-conjugate fermion pair satisfies

$$\boxed{N(f) + N(\bar{f}) = 0}. \tag{29}$$

This establishes an explicitly symmetric N-orientation for every fermion and its charge-conjugate counterpart. The present classification therefore changes the cross-species criterion used to assign the particle–antiparticle orientation, while leaving the charge-conjugation pairing between each state and its conjugate counterpart intact.

2.3 Additivity of N for Composite Particles

We extend the quantum number N to composite states additively. If a composite state H contains constituents with quantum numbers N_i, we define its total N as

$$N_H = \sum_i N_i. \tag{30}$$

For the proton, whose valence-quark content is [1, 11]

$$uud, \tag{31}$$

the additive assignment gives

$$\begin{aligned} N(p) &= N(u) + N(u) + N(d) \\ &= (+1) + (+1) + (-1) \\ &= +1. \end{aligned} \tag{32}$$

Thus,

$$N(p) = +1. \tag{33}$$

For the neutron, whose valence-quark content is [1, 11]

$$udd, \tag{34}$$

the additive assignment gives

$$
\begin{aligned}
N(n) &= N(u) + N(d) + N(d) \\
&= (+1) + (-1) + (-1) \\
&= -1.
\end{aligned} \tag{35}
$$

Hence,

$$N(n) = -1. \tag{36}$$

This result is central to the weak-isospin-based classification. The conventional Standard Model classification places both the proton and neutron among matter baryons. In the present classification, however, they possess opposite particle–antiparticle orientations,

$$\boxed{p: \; N = +1, \qquad n: \; N = -1}. \tag{37}$$

Charge conjugation gives

$$N(\bar{p}) = -1, \qquad N(\bar{n}) = +1, \tag{38}$$

so that the sign of N reverses for both conjugate pairs,

$$p \longleftrightarrow \bar{p}, \qquad n \longleftrightarrow \bar{n}. \tag{39}$$

Beyond the valence-quark representation, additional sea quark–antiquark pairs contribute zero net N under the additive assignment because each pair satisfies $N(q)+N(\bar{q}) = 0$. Gluons are $SU(2)_L$-singlet gauge fields and are assigned $N(g) = 0$ in the present extension. Consequently, within this additive bookkeeping, sea-quark-pair and gluon components do not alter the net N determined by the hadron's net quark-flavor content [1].

The same additive rule applies to other composite hadrons and provides the basis for the analysis of baryon multiplets, mesons, and particle decays in the following sections.

2.3.1 Distinction Between the Particle–Antiparticle Classification and Matter–Antimatter Terminology

In the present framework, the classification based on $N_f = 2T_{3L}(f_L)$ defines the fundamental particle–antiparticle orientation of individual particle species. By contrast, the terms matter and antimatter are retained as conventional compositional or phenomenological terminology for composite physical systems consisting of multiple particles.

This distinction becomes clear in the case of the hydrogen atom. Hydrogen consists of a proton and an electron, with

$$N(p) = +1, \qquad N(e^-) = -1. \tag{40}$$

Thus, under the present classification, a hydrogen atom contains both a positive-N particle-sector constituent and a negative-N antiparticle-sector constituent. By additivity,

$$N(\mathrm{H}) = N(p) + N(e^-) = (+1) + (-1) = 0. \tag{41}$$

Hydrogen therefore belongs to the N-neutral sector under the additive assignment.

Similarly, antihydrogen consists of an antiproton and a positron, with

$$N(\bar{p}) = -1, \qquad N(e^+) = +1. \tag{42}$$

Therefore,

$$N(\overline{\mathrm{H}}) = N(\bar{p}) + N(e^+) = (-1) + (+1) = 0. \tag{43}$$

Thus, hydrogen and antihydrogen are distinct charge-conjugate composite systems that both belong to the N-neutral sector. This also provides a simple example showing that $N = 0$ does not necessarily imply a self-conjugate state.

This structure shows that the matter–antimatter terminology and the particle–antiparticle classification are not equivalent. In the present framework,

$$\boxed{\text{particle–antiparticle classification} \neq \text{matter–antimatter terminology}} \tag{44}$$

The particle–antiparticle classification is defined at the level of individual particle species by

$$N_f = 2T_{3L}(f_L). \tag{45}$$

By contrast, terms such as matter, antimatter, hydrogen, and antihydrogen may continue to be used as conventional names describing the composition or charge-conjugate relation of composite physical systems.

Accordingly, the present framework does not treat matter and antimatter as an independent fundamental particle classification. Conventional terminology may still refer to hydrogen as matter and antihydrogen as antimatter, but these terms do not correspond respectively to the positive-N particle sector and the negative-N antiparticle sector.

The same distinction applies to ordinary atoms containing neutrons. An ordinary atom is composed of constituents satisfying

$$N(p) = +1, \qquad N(n) = -1, \qquad N(e^-) = -1. \tag{46}$$

Thus, a physical system conventionally referred to as matter may contain both particle-sector and antiparticle-sector constituents under the N-based classification.

The corresponding antiatom contains

$$N(\bar{p}) = -1, \qquad N(\bar{n}) = +1, \qquad N(e^+) = +1. \tag{47}$$

Again, the matter–antimatter terminology of the composite system is distinct from the N-based particle–antiparticle classification of its individual constituents.

Accordingly, throughout this work, the terms “matter” and “antimatter” may be retained where useful as conventional terminology for composite systems, but they are not used as the fundamental criterion for particle classification. The fundamental particle–antiparticle classification is determined by

$$N_f = 2T_{3L}(f_L). \tag{48}$$

With this distinction, the conventional statement that the observable Universe is matter dominated is not inconsistent with the global particle–antiparticle symmetry condition

$$N_{\text{tot}} = 0. \tag{49}$$

Ordinary matter itself can contain both positive-N and negative-N constituents under the weak-isospin-based classification.

2.4 Unified Classification of Particles, Baryons, and Leptons

Within the present weak-isospin-based classification, the sign of quantum number N is used not only to distinguish particles from antiparticles, but also as a unified criterion for baryon–antibaryon and lepton–antilepton orientations.

In the leptonic sector, the classification is defined by

$$\boxed{N>0: \quad \text{lepton}, \qquad N<0: \quad \text{antilepton}, \qquad N=0: \; N\text{-neutral sector}}. \tag{50}$$

Accordingly,

$$\nu: \quad N=+1 \tag{51}$$

is classified as both a particle and a lepton, whereas

$$e^-: \quad N=-1 \tag{52}$$

is classified as both an antiparticle and an antilepton.
For the corresponding charge-conjugate states,

$$e^+: \quad N=+1 \tag{53}$$

is a particle and a lepton, whereas

$$\bar{\nu}: \quad N=-1 \tag{54}$$

is an antiparticle and an antilepton.
Thus,

$$\nu,\ e^+: \quad \text{particle/lepton sector}, \tag{55}$$

whereas

$$e^-,\ \bar{\nu}: \quad \text{antiparticle/antilepton sector}. \tag{56}$$

The same principle applies to baryonic composite states constructed from more general combinations of quark and antiquark constituents. For such quark configurations, the baryon–antibaryon orientation in the present classification is determined by the sign of the total additive N,

$$\boxed{N>0: \quad \text{baryon}, \qquad N<0: \quad \text{antibaryon}, \qquad N=0: \quad N\text{-neutral sector}}. \tag{57}$$

Using the proton valence-quark content uud [1, 11],

$$N(p)=+1, \tag{58}$$

and therefore the proton is classified as both a particle and a baryon.
Using the neutron valence-quark content udd [1, 11],

$$N(n)=-1, \tag{59}$$

so the neutron is classified as both an antiparticle and an antibaryon.
For the charge-conjugate states,

$$N(\bar{p}) = -1, \tag{60}$$

and therefore the antiproton is classified as an antiparticle and an antibaryon, whereas

$$N(\bar{n}) = +1, \tag{61}$$

and therefore the antineutron is classified as a particle and a baryon.

The resulting assignments are

$$\boxed{p: \ \text{particle/baryon}, \qquad n: \ \text{antiparticle/antibaryon}}, \tag{62}$$

and

$$\boxed{\bar{p}: \ \text{antiparticle/antibaryon}, \qquad \bar{n}: \ \text{particle/baryon}}. \tag{63}$$

Thus, the particle–antiparticle, baryon–antibaryon, and lepton–antilepton orientations are unified by a single signed quantum number,

$$\boxed{\begin{aligned} \mathrm{sgn}(N) \quad \Longrightarrow \quad & \text{particle–antiparticle, baryon–antibaryon,} \\ & \text{and lepton–antilepton orientation} \end{aligned}}. \tag{64}$$

2.5 Massive Dirac Fermions and the Species-Level Definition of $N = 2T_{3L}$

An important issue arises when the weak-isospin-based classification is applied to massive Dirac fermions. In the Standard Model, T_{3L} acts on the left-handed weak-isospin doublet [1,7]. For example,

$$T_{3L}(e_L) = -\frac{1}{2}, \tag{65}$$

and therefore

$$N(e^-) = 2T_{3L}(e_L) = -1. \tag{66}$$

The right-handed electron, however, is an $SU(2)_L$ singlet and satisfies

$$T_{3L}(e_R) = 0. \tag{67}$$

Accordingly, the relation

$$N = 2T_{3L} \tag{68}$$

is not interpreted here as an $SU(2)_L$ generator acting independently on every chiral component of a Dirac fermion.

Instead, we determine the N-orientation of a fermion species from the position occupied by its left-handed component within the corresponding weak-isospin doublet. Thus,

$$\boxed{N(e^-) \equiv 2T_{3L}(e_L) = -1}, \tag{69}$$

and we assign this value $N = -1$ to the physical electron as a single fermion species.

Similarly,

$$N(u) \equiv 2T_{3L}(u_L) = +1, \tag{70}$$

and

$$N(d) \equiv 2T_{3L}(d_L) = -1. \tag{71}$$

This does not imply that

$$2T_{3L}(e_R) = -1. \tag{72}$$

Within the Standard Model,

$$T_{3L}(e_R) = 0. \tag{73}$$

Rather, the left-handed weak-isospin orientation determines the N-classification of the entire fermion species.

This distinction is important for massive Dirac fermions. A physical electron is not a composite state made of an e_L constituent and an e_R constituent. It is a single Dirac fermion with left- and right-handed chiral components [7]. Consequently, the quantum number of the electron is not obtained from a constituent sum such as

$$N(e_L) + N(e_R). \tag{74}$$

In this sense, the relation $N = 2T_{3L}$ defines the particle–antiparticle orientation of the physical fermion species through the weak-isospin orientation of its left-handed component.

2.6 Extension to an Exact Additive Charge and a Possible Left–Right Completion

A stronger theoretical requirement arises if N is promoted from a species-level classification quantum number to an exact continuous additive charge acting directly on both left- and right-handed fields. In this case, consistency with the mass term of a massive Dirac fermion must be examined.

The Dirac mass term has the form

$$\mathcal{L}_m = -m_f \left(\bar{f}_L f_R + \bar{f}_R f_L \right). \tag{75}$$

Let

$$N(f_L) = N_L, \qquad N(f_R) = N_R. \tag{76}$$

Under a continuous N transformation, the bilinear

$$\bar{f}_L f_R \tag{77}$$

carries the charge

$$N_R - N_L. \tag{78}$$

Therefore, invariance of the Dirac mass term under an exact additive N symmetry requires

$$N_L = N_R. \tag{79}$$

This condition requires a corresponding orientation structure in the right-handed fermion sector when the weak-isospin-based classification is extended to a chirality-independent exact additive charge.

A natural possibility is a left–right symmetric completion [12, 13]. If the right-handed fermions form $SU(2)_R$ doublets,

$$\begin{pmatrix} u_R \\ d_R \end{pmatrix}, \qquad \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}, \tag{80}$$

with

$$T_{3R}(u_R) = T_{3R}(\nu_R) = +\frac{1}{2}, \tag{81}$$

and

$$T_{3R}(d_R) = T_{3R}(e_R) = -\frac{1}{2}, \tag{82}$$

then the quantum number N can be extended to

$$N = 2(T_{3L} + T_{3R}). \tag{83}$$

For the left-handed electron,

$$T_{3L}(e_L) = -\frac{1}{2}, \qquad T_{3R}(e_L) = 0, \tag{84}$$

and therefore

$$N(e_L) = 2\,[T_{3L}(e_L) + T_{3R}(e_L)] = 2\left(-\frac{1}{2} + 0\right) = -1. \tag{85}$$

For the right-handed electron,

$$T_{3L}(e_R) = 0, \qquad T_{3R}(e_R) = -\frac{1}{2}, \tag{86}$$

and therefore

$$N(e_R) = 2\,[T_{3L}(e_R) + T_{3R}(e_R)] = 2\left(0 - \frac{1}{2}\right) = -1. \tag{87}$$

Hence,

$$N_L = N_R = -1. \tag{88}$$

Likewise,

$$N(u_L) = N(u_R) = +1, \tag{89}$$

and

$$N(d_L) = N(d_R) = -1. \tag{90}$$

Thus, the fermion-species orientation defined by $N = 2T_{3L}$ acquires the chirality-independent additive form

$$\boxed{N = 2(T_{3L} + T_{3R})} \tag{91}$$

in a left–right symmetric realization.

This unified form provides a possible chirality-independent realization of the N assignment within the gauge structure of the well-studied class of left–right symmetric theories [12, 13]. Such theories naturally contain right-handed fermion doublets, right-handed neutrinos, and right-handed charged-current interactions mediated by a W_R boson.

Although no $SU(2)_R$ gauge interaction has yet been experimentally confirmed, direct LHC searches for W_R bosons and heavy right-handed neutrinos have placed strong constraints on the corresponding left–right-symmetric-model parameter space [14,15]. The discovery of such a sector with the corresponding left–right doublet structure and N assignments would provide an independent physical realization of the chirality-independent N structure proposed here.

3 Microscopic Consistency Tests of N Conservation in Particle Transformations and Decays

3.1 First-Generation Weak Interactions and Neutron Beta Decay

In the weak-isospin-based classification introduced in Sec. 2, the first-generation fermions carry

$$N(u) = +1, \qquad N(d) = -1, \tag{92}$$

and

$$N(\nu_e) = +1, \qquad N(e^-) = -1. \tag{93}$$

The corresponding charge-conjugate states carry the opposite values,

$$N(\bar{u}) = -1, \qquad N(\bar{d}) = +1, \tag{94}$$

and

$$N(\bar{\nu}_e) = -1, \qquad N(e^+) = +1. \tag{95}$$

Charged-current weak interactions connect the upper and lower members of the weak-isospin doublets [1,7].

Consider the representative charged-current quark transition

$$d \to u + W^{-*}, \qquad W^{-*} \to e^- + \bar{\nu}_e, \tag{96}$$

where W^{-*} denotes an off-shell charged weak boson.

The initial state carries $N(d) = -1$, whereas the outgoing up quark carries $N(u) = +1$. Extending N additively to the charged gauge sector, conservation at the vertex fixes the charged-boson assignment through

$$-1 = (+1) + N(W^-), \tag{97}$$

which gives

$$N(W^-) = -2. \tag{98}$$

The conjugate charged-current transition gives

$$N(W^+) = +2. \tag{99}$$

The two-unit transfer follows directly from the opposite weak-isospin orientations of the upper and lower fermion states,

$$(+1) - (-1) = 2. \tag{100}$$

The leptonic charged-current vertex gives the same result. For example,

$$W^- \to e^- + \bar{\nu}_e \tag{101}$$

satisfies

$$-2 = (-1) + (-1). \tag{102}$$

Neutron beta decay provides a representative composite-particle test,

$$n \to p + e^- + \bar{\nu}_e. \tag{103}$$

Using

$$N(n) = -1, \qquad N(p) = +1, \tag{104}$$

the final state carries

$$\begin{aligned} N_{\text{final}} &= N(p) + N(e^-) + N(\bar{\nu}_e) \\ &= (+1) + (-1) + (-1) \\ &= -1. \end{aligned} \tag{105}$$

Hence,

$$N_{\text{initial}} = N_{\text{final}} = -1. \tag{106}$$

At the quark level, the same process contains

$$d \to u + W^{-*}, \qquad W^{-*} \to e^- + \bar{\nu}_e, \tag{107}$$

for which

$$-1 = (+1) + (-2), \qquad -2 = (-1) + (-1). \tag{108}$$

Thus, the constituent-level weak transition and the complete neutron decay exhibit the same additive N-conservation structure.

3.2 Higher-Generation Fermions and Gauge-Interaction Tests

The weak-isospin assignments repeat across the three fermion generations,

$$N(u) = N(c) = N(t) = +1, \tag{109}$$

$$N(d) = N(s) = N(b) = -1, \tag{110}$$

and

$$N(\nu_e) = N(\nu_\mu) = N(\nu_\tau) = +1, \tag{111}$$

$$N(e^-) = N(\mu^-) = N(\tau^-) = -1. \tag{112}$$

Consequently, charged-current transitions between an up-type and a down-type fermion exhibit the same two-unit N transfer in every generation. CKM mixing changes the amplitudes of quark flavor transitions but does not alter this N structure because all up-type quarks carry $N = +1$ and all down-type quarks carry $N = -1$ [1].

Neutral gauge interactions preserve N because they couple a fermion to a state with the same N orientation or create a fermion–antifermion pair with opposite N. Table 2 summarizes representative processes and vertices.

Table 2: Representative fermion and gauge-interaction tests of N conservation.

Vertex / Process	N_{initial}	Final-state or vertex N balance	Result
$W^+ \to e^+ + \nu_e$	$+2$	$(+1)+(+1)=+2$	Conserved
$W^- \to e^- + \bar{\nu}_e$	-2	$(-1)+(-1)=-2$	Conserved
$W^+ \to u + \bar{d}$	$+2$	$(+1)+(+1)=+2$	Conserved
$W^- \to d + \bar{u}$	-2	$(-1)+(-1)=-2$	Conserved
$s \to u + W^{-*}$	-1	$(+1)+(-2)=-1$	Conserved
$c \to s + W^{+*}$	$+1$	$(-1)+(+2)=+1$	Conserved
$b \to c + W^{-*}$	-1	$(+1)+(-2)=-1$	Conserved
$t \to b + W^+$	$+1$	$(-1)+(+2)=+1$	Conserved
$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$	-1	$(-1)+(-1)+(+1)=-1$	Conserved
$\tau^- \to \mu^- + \bar{\nu}_\mu + \nu_\tau$	-1	$(-1)+(-1)+(+1)=-1$	Conserved
$Z^0 \to e^- + e^+$	0	$(-1)+(+1)=0$	Conserved
$Z^0 \to \nu + \bar{\nu}$	0	$(+1)+(-1)=0$	Conserved
$Z^0 \to b + \bar{b}$	0	$(-1)+(+1)=0$	Conserved
$\gamma f \bar{f}$	–	$N(f)+N(\bar{f})+N(\gamma)=0$	Conserved
$g q \bar{q}$	–	$N(q)+N(\bar{q})+N(g)=0$	Conserved
$W^+W^-\gamma$	–	$(+2)+(-2)+0=0$	Conserved
$W^+W^-Z^0$	–	$(+2)+(-2)+0=0$	Conserved
$W^+W^-W^+W^-$	–	$(+2)+(-2)+(+2)+(-2)=0$	Conserved

Here $W^{\pm *}$ denotes an off-shell charged weak boson in flavor-changing transitions for which emission of a real $W^\pm$ is kinematically forbidden [1,7].

Within the additive extension of N to the gauge sector, the neutral gauge bosons carry

$$\boxed{N(Z^0)=N(\gamma)=N(g)=0}, \tag{113}$$

whereas the charged weak gauge bosons carry

$$N(W^+)=+2, \qquad N(W^-)=-2. \tag{114}$$

The representative electroweak and strong-interaction vertices listed above are standard interactions of the Standard Model [1, 7]. With the N assignments introduced here, they exhibit the same additive N balance throughout.

Within the species-level classification adopted here, all three active weak-flavor neutrino states carry $N=+1$, so ordinary flavor oscillations among these states [1] do not change N.

$$N(\nu_e)=N(\nu_\mu)=N(\nu_\tau)=+1. \tag{115}$$

3.3 Composite Hadrons and Hadronic Decays

The present framework extends the species-level quantum number N to composite states through the additive relation

$$N_H=\sum_i N_i. \tag{116}$$

For physical three-quark hadrons, let U denote an up-type valence quark and D a down-type valence quark. Their assignments are

$$N(U) = +1, \qquad N(D) = -1, \tag{117}$$

while the corresponding antiquarks carry

$$N(\bar{U}) = -1, \qquad N(\bar{D}) = +1. \tag{118}$$

For a three-quark valence configuration, let n_U and n_D denote the nonnegative numbers of up-type and down-type valence quarks. Then

$$N_H = n_U N(U) + n_D N(D) = n_U - n_D. \tag{119}$$

Since

$$n_U + n_D = 3, \tag{120}$$

the possible values are

$$N_H = +3,\ +1,\ -1,\ -3. \tag{121}$$

Thus, a three-quark valence configuration always has a nonzero N orientation.

As a representative example, the Δ^{++} has the valence-quark content uuu [1,11], and therefore

$$N(\Delta^{++}) = +3. \tag{122}$$

Its strong decay

$$\Delta^{++} \to p + \pi^+ \tag{123}$$

satisfies

$$+3 = (+1) + (+2). \tag{124}$$

The same additive rule applies to other baryonic and mesonic states. Table 3 summarizes representative assignments and decay tests [1,11].

Table 3: Representative composite-hadron assignments and decay tests of N conservation.

State / Process	**Initial-state / assigned N**	**Final-state N balance**	**Result**
$p(uud)$	$+1$	–	Assignment
$n(udd)$	-1	–	Assignment
$\Delta^{++}(uuu) \to p + \pi^+$	$+3$	$(+1) + (+2) = +3$	Conserved
$\Lambda^0(uds) \to p + \pi^-$	-1	$(+1) + (-2) = -1$	Conserved
$\pi^- \to \mu^- + \bar{\nu}_\mu$	-2	$(-1) + (-1) = -2$	Conserved
$\pi^+ \to \mu^+ + \nu_\mu$	$+2$	$(+1) + (+1) = +2$	Conserved
$K^+(u\bar{s}) \to \mu^+ + \nu_\mu$	$+2$	$(+1) + (+1) = +2$	Conserved
$K^0(d\bar{s})$	0	–	Neutral N sector
$\bar{K}^0(s\bar{d})$	0	–	Neutral N sector
$K^0 \to \pi^+ + \pi^-$	0	$(+2) + (-2) = 0$	Conserved

For a quark–antiquark meson, the possible values are

$$N = +2,\ -2,\ 0. \tag{125}$$

Charged mesons such as

$$\pi^+ = u\bar{d}, \qquad \pi^- = d\bar{u} \tag{126}$$

carry

$$N(\pi^+) = +2, \qquad N(\pi^-) = -2, \tag{127}$$

whereas neutral mesons can belong to the $N = 0$ sector. In particular,

$$N(K^0) = N(\bar{K}^0) = 0. \tag{128}$$

Thus, N does not distinguish every charge-conjugate neutral meson pair by sign. Instead, both members of such a pair can lie in the neutral $N = 0$ sector.

The examples in Table 3 show that the additive constituent assignment remains consistent across representative strong and weak hadronic decays.

3.4 Transfer of N by Gauge Bosons

Within the additive extension of N to the gauge sector, the charged weak gauge bosons carry

$$N(W^+) = +2, \qquad N(W^-) = -2. \tag{129}$$

The charged-current interaction connects the upper and lower members of weak-isospin doublets [1,7]. Within the additive extension of N introduced here, their two-unit separation,

$$|\Delta N| = 2, \tag{130}$$

fixes

$$N(W^+) = +2, \qquad N(W^-) = -2. \tag{131}$$

These assignments are consistently reproduced by the fermionic charged-current channels summarized in Table 2.

The neutral electroweak, electromagnetic, and strong gauge vertices do not transfer a fermion between the $N = +1$ and $N = -1$ weak-isospin orientations. The corresponding vertices

$$Zf\bar{f}, \qquad \gamma f\bar{f}, \qquad gq\bar{q} \tag{132}$$

are consistent with

$$N(Z) = 0, \qquad N(\gamma) = 0, \qquad N(g) = 0. \tag{133}$$

For a neutral gauge boson $V = Z, \gamma, g$, the vertex balance takes the form

$$N(f) + N(\bar{f}) + N(V) = 0, \tag{134}$$

or, for the strong interaction,

$$N(q) + N(\bar{q}) + N(g) = 0. \tag{135}$$

The gauge-boson assignments can therefore be summarized as

$$W^+ : +2, \qquad W^- : -2, \qquad Z, \gamma, g : 0. \tag{136}$$

Thus, the charged weak interaction transfers the two units of N separating the upper and lower components of a fermion doublet, whereas neutral-current, electromagnetic, and strong gauge interactions preserve the fermion N-orientation.

3.5 Charge-Conjugate Decays and Sign-Reversed N Balance

Charge conjugation reverses the sign of N,

$$C: \quad N \to -N. \tag{137}$$

Suppose an N-conserving process satisfies

$$N_{\text{initial}} = \sum_i N_{\text{final},i}. \tag{138}$$

For any physically allowed charge-conjugate process, the N assignments are obtained by reversing the sign of N for every charge-conjugate state.

The corresponding charge-conjugate N-balance is

$$-N_{\text{initial}} = \sum_i \left(-N_{\text{final},i}\right). \tag{139}$$

For neutron beta decay,

$$n \to p + e^- + \bar{\nu}_e, \tag{140}$$

the relation is

$$-1 = (+1) + (-1) + (-1). \tag{141}$$

The charge-conjugate process

$$\bar{n} \to \bar{p} + e^+ + \nu_e \tag{142}$$

satisfies

$$+1 = (-1) + (+1) + (+1). \tag{143}$$

Thus, whenever the corresponding charge-conjugate process is physically allowed, its N-balance has the same form with all N signs reversed.

3.6 Chirality, Dirac Mass, and the Scope of N Conservation

As established in Sec. 2, the basic species-level quantum number is defined from the left-handed weak-isospin component,

$$\boxed{N_f = 2T_{3L}(f_L)}. \tag{144}$$

For a massive Dirac fermion, this relation assigns N to the physical fermion species as a whole. It does not apply $N = 2T_{3L}$ independently to the right-handed $SU(2)_L$-singlet component [1,7].

For example,

$$N(e^-) = -1, \qquad N(u) = +1, \qquad N(d) = -1. \tag{145}$$

The assignments $N(u) = +1$ and $N(d) = -1$ likewise apply to the corresponding fermion species as a whole and are not obtained by applying $N = 2T_{3L}$ separately to their right-handed $SU(2)_L$-singlet components.

If N is promoted to an exact continuous additive charge acting directly on both chiral fields, the Dirac mass term

$$\mathcal{L}_m = -m_f \left(\bar{f}_L f_R + \bar{f}_R f_L\right) \tag{146}$$

requires

$$N_L = N_R. \tag{147}$$

A possible realization is provided by the left–right symmetric gauge structure, in which right-handed fermions are organized into corresponding $SU(2)_R$ multiplets [12, 13].

Within the present framework, this permits the species-level relation to be extended as

$$\boxed{N = 2(T_{3L} + T_{3R})}, \tag{148}$$

for which

$$N(f_L) = N(f_R) \tag{149}$$

can hold for a massive Dirac fermion.

In this realization, each Dirac mass bilinear is neutral under the additive N charge because

$$N(\bar{f}_L f_R) = N_R - N_L = 0, \tag{150}$$

and

$$N(\bar{f}_R f_L) = N_L - N_R = 0. \tag{151}$$

Representative Higgs decay channels include [1]

$$h \to f + \bar{f}, \qquad h \to W^+ W^{-*}, \qquad h \to ZZ^*, \qquad h \to \gamma\gamma. \tag{152}$$

For the physical Higgs boson,

$$Q(h) = B(h) = L(h) = 0, \tag{153}$$

and the extended additive relation therefore gives

$$N(h) = 0. \tag{154}$$

This assignment is consistent with the representative Higgs decay channels listed above. For the fermionic channel,

$$N(f) + N(\bar{f}) = 0, \tag{155}$$

while for the representative bosonic channels,

$$N(W^+) + N(W^-) = 0, \qquad 2N(Z) = 0, \qquad 2N(\gamma) = 0. \tag{156}$$

The extension of N to an exact field-theoretic symmetry of the complete theory is a stronger theoretical question. In a left–right realization, the Yukawa interactions, scalar sector, and vacuum structure must all be compatible with the extended N symmetry.

The microscopic transformations examined in this section are mutually consistent with an additive N structure across first-generation beta decay, higher-generation flavor-changing transitions, hadron and meson decays, charge-conjugate processes, and gauge-mediated interactions.

4 Macroscopic Consistency Tests: N Conservation and Redistribution in Stellar Fusion and the Early Universe

4.1 The Proton–Proton Chain and Quantum Number N Conservation in Stellar Fusion

In the Sun and other low-mass main-sequence stars, the proton–proton chain is the principal hydrogen-burning energy source [16]. In the weak-isospin-based classification, the proton and neutron carry

$$N(p) = +1, \qquad N(n) = -1, \tag{157}$$

while the positron and electron neutrino carry

$$N(e^+) = +1, \qquad N(\nu_e) = +1. \tag{158}$$

A principal initiating reaction of the proton–proton chain is

$$p + p \to d + e^+ + \nu_e. \tag{159}$$

Since the deuteron consists of one proton and one neutron,

$$N(d) = N(p) + N(n) = (+1) + (-1) = 0. \tag{160}$$

The total initial value of N is therefore

$$N_{\text{initial}} = N(p) + N(p) = +2, \tag{161}$$

whereas the final state carries

$$\begin{aligned} N_{\text{final}} &= N(d) + N(e^+) + N(\nu_e) \\ &= 0 + (+1) + (+1) \\ &= +2. \end{aligned} \tag{162}$$

Hence,

$$N_{\text{initial}} = N_{\text{final}}. \tag{163}$$

At the quark level, this reaction contains a charged-current weak transition in which an up-type quark inside one proton is converted into a down-type quark. As the baryonic state changes from a proton with $N = +1$ to a neutron with $N = -1$, two units of positive N are transferred to the positron and neutrino sector.

The next step,

$$d + p \to {}^3\text{He} + \gamma, \tag{164}$$

also preserves N. Since ^{3}He contains two protons and one neutron,

$$N({}^3\text{He}) = 2N(p) + N(n) = 2(+1) + (-1) = +1. \tag{165}$$

Thus,

$$N(d) + N(p) = 0 + (+1) = +1. \tag{166}$$

Because the photon carries

$$N(\gamma) = 0, \tag{167}$$

the final state has

$$(+1) + 0 = +1. \tag{168}$$

Therefore N is conserved in this step as well.

A representative final reaction of the proton–proton chain is

$$^3\text{He} + {}^3\text{He} \to {}^4\text{He} + p + p. \tag{169}$$

The ^{4}He nucleus contains two protons and two neutrons, so

$$N(^4\text{He}) = 2(+1) + 2(-1) = 0. \tag{170}$$

The initial state carries

$$N_{\text{initial}} = (+1) + (+1) = +2, \tag{171}$$

whereas the final state carries

$$N_{\text{final}} = 0 + (+1) + (+1) = +2. \tag{172}$$

Thus,

$$N(^3\text{He}) + N(^3\text{He}) = N(^4\text{He}) + 2N(p). \tag{173}$$

The net proton–proton chain can be written as [16]

$$4p \to {}^4\text{He} + 2e^+ + 2\nu_e + \text{energy}. \tag{174}$$

The corresponding N balance is

$$4(+1) = 0 + 2(+1) + 2(+1), \tag{175}$$

or

$$+4 = +4. \tag{176}$$

Thus, the representative proton–proton-chain sequence and its net reaction preserve the additive N balance.

4.2 N Redistribution and Neutrino Emission in Stellar Interiors

An important feature of the proton–proton chain is not only that the total value of N is conserved, but also that N is redistributed among different physical sectors.

The ^{4}He nucleus carries

$$N(^4\text{He}) = 0. \tag{177}$$

Consequently, when four protons are converted into helium-4, the four units of positive N initially carried by the nuclear baryonic constituents are transferred to the positron and neutrino sector.

For

$$4p \to {}^4\text{He} + 2e^+ + 2\nu_e, \tag{178}$$

the baryonic sector alone changes as

$$N_{\text{baryonic}}: \qquad +4 \to 0. \tag{179}$$

At the same time, the leptonic sector receives

$$2N(e^+) + 2N(\nu_e) = +4. \tag{180}$$

Thus the decrease of baryonic N is not a disappearance of N, but a redistribution,

$$\boxed{\text{baryonic sector} \longrightarrow \text{leptonic sector}}. \tag{181}$$

The positrons produced in the stellar plasma subsequently annihilate with surrounding electrons,

$$e^+ + e^- \to \gamma + \gamma. \tag{182}$$

In the weak-isospin-based classification,

$$N(e^+) = +1, \qquad N(e^-) = -1, \tag{183}$$

so that

$$(+1) + (-1) = 0. \tag{184}$$

Since

$$N(\gamma) + N(\gamma) = 0, \tag{185}$$

the annihilation process also conserves N,

$$0 = 0. \tag{186}$$

Including positron annihilation, the effective stellar reaction may be written as

$$4p + 2e^- \to {}^4\text{He} + 2\,\nu_e + \text{energy}. \tag{187}$$

The initial state carries

$$4(+1) + 2(-1) = +2, \tag{188}$$

while the final state carries

$$0 + 2(+1) = +2. \tag{189}$$

Hence,

$$4N(p) + 2N(e^-) = N({}^4\text{He}) + 2N(\nu_e). \tag{190}$$

This form directly shows how N is redistributed between nuclear matter and the lepton sector during stellar fusion.

Because the neutrinos produced in proton–proton-chain reactions escape from the Sun and similar main-sequence stars with negligible trapping [1, 16], the value of N contained within stellar matter alone can change with time. When the emitted neutrino flux is included, however, the additive N balance of the complete system is maintained. Subsequent flavor oscillations of the emitted solar neutrinos do not alter this N balance because all three active weak-flavor neutrino states carry $N = +1$.

Stellar fusion therefore provides a macroscopic example of both N conservation and N redistribution.

4.3 Proton–Neutron Weak Equilibrium in the Early Universe

During the nucleon weak-equilibrium epoch preceding Big Bang nucleosynthesis, protons and neutrons were continuously interconverted through weak interactions [1,17]. Representative reactions include

$$n + \nu_e \longleftrightarrow p + e^-, \tag{191}$$

$$n + e^+ \longleftrightarrow p + \bar{\nu}_e, \tag{192}$$

and

$$n \longleftrightarrow p + e^- + \bar{\nu}_e. \tag{193}$$

The N balance can be verified directly in each process.
For the first reaction,

$$N(n) + N(\nu_e) = (-1) + (+1) = 0, \tag{194}$$

while

$$N(p) + N(e^-) = (+1) + (-1) = 0. \tag{195}$$

Thus,

$$n + \nu_e \longleftrightarrow p + e^- \tag{196}$$

conserves N in both directions.
For the second reaction,

$$N(n) + N(e^+) = (-1) + (+1) = 0, \tag{197}$$

and

$$N(p) + N(\bar{\nu}_e) = (+1) + (-1) = 0. \tag{198}$$

Hence,

$$\boxed{n + e^+ \longleftrightarrow p + \bar{\nu}_e} \tag{199}$$

also conserves N.
Similarly, neutron beta decay satisfies

$$N(n) = -1, \tag{200}$$

and

$$N(p) + N(e^-) + N(\bar{\nu}_e) = (+1) + (-1) + (-1) = -1. \tag{201}$$

Therefore,

$$\boxed{n \longleftrightarrow p + e^- + \bar{\nu}_e} \tag{202}$$

obeys the same conservation structure.

During the nucleon weak-equilibrium epoch, the forward and reverse weak reactions occurred rapidly compared with the cosmic expansion and maintained the proton–neutron system near chemical equilibrium [1, 17].

Within this nucleon regime, for negligible lepton chemical potentials, the equilibrium neutron-to-proton ratio is approximately

$$\frac{n_n}{n_p} \simeq \exp\left(-\frac{\Delta m_{np}}{T}\right). \tag{203}$$

Therefore, for temperatures satisfying

$$T \gg \Delta m_{np}, \tag{204}$$

the proton and neutron number densities approximately satisfy

$$n_p \simeq n_n. \tag{205}$$

The same residual proton–neutron population is described differently in the conventional Standard Model baryon-number bookkeeping and in the weak-isospin-based classification.

In the conventional classification, both the proton and neutron carry positive baryon number,

$$B(p) = B(n) = +1, \tag{206}$$

whereas the antiproton and antineutron carry

$$B(\bar{p}) = B(\bar{n}) = -1. \tag{207}$$

The corresponding net conventional baryonic number density is therefore

$$n_{\rm SM}^{\rm baryonic} = (n_p - n_{\bar{p}}) + (n_n - n_{\bar{n}}). \tag{208}$$

For the residual nucleon population relevant to the later weak-equilibrium and Big Bang nucleosynthesis regime, conventional antinucleon abundances are negligible compared with the surviving nucleon abundances,

$$n_{\bar{p}}, n_{\bar{n}} \ll n_p, n_n. \tag{209}$$

Accordingly,

$$\boxed{n_{\rm SM}^{\rm baryonic} \simeq n_p + n_n > 0}. \tag{210}$$

Thus, in the conventional baryon-number classification, the proton and neutron contributions enter with the same positive sign.

In the weak-isospin-based classification, by contrast,

$$N(p) = +1, \qquad N(n) = -1, \tag{211}$$

while

$$N(\bar{p}) = -1, \qquad N(\bar{n}) = +1. \tag{212}$$

The proton therefore belongs to the positive-N baryonic orientation, whereas the neutron belongs to the negative-N antibaryonic orientation in the present classification.

The corresponding baryonic N-number density is

$$n_N^{\text{baryonic}} = (n_p - n_{\bar{p}}) + (n_{\bar{n}} - n_n). \tag{213}$$

When conventional antinucleon abundances are negligible, this becomes

$$n_N^{\text{baryonic}} \simeq n_p - n_n. \tag{214}$$

Since

$$n_p \simeq n_n \tag{215}$$

in the high-temperature nucleon weak-equilibrium regime,

$$\boxed{n_N^{\text{baryonic}} \simeq n_p - n_n \simeq 0}. \tag{216}$$

The same residual proton–neutron population therefore has two different signed descriptions:

$$\boxed{n_{\text{SM}}^{\text{baryonic}} \simeq n_p + n_n > 0, \qquad n_N^{\text{baryonic}} \simeq n_p - n_n \simeq 0}. \tag{217}$$

In the conventional Standard Model baryon-number bookkeeping, the proton and neutron contributions add with the same sign. In the weak-isospin-based classification, the positive-N proton contribution and the negative-N neutron contribution nearly cancel in this high-temperature residual nucleon regime.

Therefore,

$$n_p \simeq n_n \quad \Longrightarrow \quad n_N^{\text{baryonic}} \simeq n_p - n_n \simeq 0 \tag{218}$$

describes a residual nucleon sector with an approximately vanishing baryonic N-number density. This relation does not by itself establish primordial or global baryon–antibaryon symmetry, because it concerns the later residual nucleon population rather than the earlier origin of the particle–antiparticle abundance differences.

4.4 Weak Freeze-Out, Baryonic N Imbalance, and Redistribution of Quantum Number N

During the nucleon weak-equilibrium epoch of the early Universe, protons and neutrons were continuously interconverted through weak interactions. For negligible lepton chemical potentials, the equilibrium neutron-to-proton ratio is approximately given by

$$\frac{n_n}{n_p} \simeq \exp\left(-\frac{\Delta m_{np}}{T}\right), \qquad \Delta m_{np} = m_n - m_p, \tag{219}$$

where T denotes the temperature [1, 17].

At sufficiently high temperatures, n_n/n_p can approach unity. As the Universe cools, however, the neutron-to-proton ratio decreases because

$$m_n > m_p. \tag{220}$$

When the weak-interaction rate becomes too small relative to the cosmic expansion rate, the proton–neutron system can no longer continue to track its equilibrium ratio and undergoes weak freeze-out [1, 17].

At this stage, it is useful to distinguish the conventional baryon asymmetry from the baryonic N imbalance defined by the weak-isospin-based classification.

In the conventional baryon-number classification, both the proton and neutron carry

$$B = +1, \tag{221}$$

whereas the antiproton and antineutron carry

$$B = -1. \tag{222}$$

For the residual nucleon population considered here, the conventional baryon-to-photon asymmetry parameter can be written as

$$\eta_B^{\rm conv} \equiv \frac{(n_p - n_{\bar{p}}) + (n_n - n_{\bar{n}})}{n_\gamma}. \tag{223}$$

[1,2].

By contrast, in the weak-isospin-based classification,

$$N(p) = +1, \qquad N(n) = -1, \tag{224}$$

while

$$N(\bar{p}) = -1, \qquad N(\bar{n}) = +1. \tag{225}$$

The corresponding baryonic N imbalance may therefore be defined as

$$\eta_B^N \equiv \frac{(n_p - n_{\bar{p}}) + (n_{\bar{n}} - n_n)}{n_\gamma}. \tag{226}$$

For the residual nucleon population relevant to Big Bang nucleosynthesis, conventional antinucleon abundances are negligible compared with the surviving nucleon abundances,

$$n_{\bar{p}}, n_{\bar{n}} \ll n_p, n_n. \tag{227}$$

The two quantities then reduce approximately to

$$\eta_B^{\rm conv} \simeq \frac{n_p + n_n}{n_\gamma}, \tag{228}$$

and

$$\eta_B^N \simeq \frac{n_p - n_n}{n_\gamma}. \tag{229}$$

Thus, the same physical proton and neutron populations enter the two classifications through different signed combinations:

$$\boxed{\eta_B^{\rm conv} \propto n_p + n_n, \qquad \eta_B^N \propto n_p - n_n}. \tag{230}$$

Here, η_B^N characterizes the baryonic N imbalance in the weak-isospin-based classification and is distinct from the conventional baryon-to-photon asymmetry parameter.

As the Universe cools and the neutron-to-proton ratio decreases, the baryonic contribution to the additive quantum number N also changes. A change in the baryonic N imbalance, however, does not require the generation of a new total N for the complete system.

This can be seen directly from free-neutron beta decay,

$$n \to p + e^- + \bar{\nu}_e. \tag{231}$$

The initial neutron carries

$$N(n) = -1, \tag{232}$$

whereas the final-state proton carries

$$N(p) = +1. \tag{233}$$

The baryonic sector therefore changes by

$$\Delta N_{\text{baryonic}} = +2. \tag{234}$$

At the same time, the accompanying electron and electron antineutrino carry

$$N(e^-) = -1, \qquad N(\bar{\nu}_e) = -1, \tag{235}$$

so that

$$\Delta N_{\text{leptonic}} = -2. \tag{236}$$

Consequently, the complete process satisfies

$$\boxed{\Delta N_{\text{tot}} = \Delta N_{\text{baryonic}} + \Delta N_{\text{leptonic}} = 0}. \tag{237}$$

Similarly, the charged-current conversion

$$p + e^- \to n + \nu_e \tag{238}$$

gives

$$\Delta N_{\text{baryonic}} = -2, \qquad \Delta N_{\text{leptonic}} = +2, \tag{239}$$

and hence

$$\Delta N_{\text{tot}} = 0. \tag{240}$$

The proton–neutron evolution of the early Universe can therefore be described as a redistribution of N among different physical sectors rather than as the creation or destruction of the total additive N quantum number:

$$\boxed{\text{baryonic } N \quad \longleftrightarrow \quad \text{leptonic } N}. \tag{241}$$

In particular,

$$\boxed{\eta_B^N \neq 0 \quad \not\Rightarrow \quad N_{\text{tot}} \neq 0} \tag{242}$$

because a nonzero baryonic N imbalance can be accompanied by an opposite N contribution in other sectors while the total additive N quantum number remains conserved.

Weak freeze-out and the subsequent decay of free neutrons therefore modify the proton–neutron composition of the residual nucleon population and the distribution of N among different sectors. The surviving protons and neutrons are subsequently reorganized into light nuclei during Big Bang nucleosynthesis, whose constituent-level N-conservation structure is examined in the following subsection.

4.5 Big Bang Nucleosynthesis and Quantum Number N Conservation in Nuclear Formation

After weak freeze-out and further cooling through the deuterium bottleneck, the surviving neutrons and protons began to assemble efficiently into light nuclei [1, 17]. Nearly all surviving neutrons ultimately became bound in helium-4, while smaller primordial abundances of deuterium, helium-3, and other light nuclei remained [1].

The deuteron contains one proton and one neutron,

$$d: \quad p + n, \tag{243}$$

and therefore

$$N(d) = +1 - 1 = 0. \tag{244}$$

Tritium contains one proton and two neutrons,

$$^3\mathrm{H}: \quad p + n + n, \tag{245}$$

so

$$N(^3\mathrm{H}) = (+1) + (-1) + (-1) = -1. \tag{246}$$

Helium-3 contains two protons and one neutron,

$$^3\mathrm{He}: \quad p + p + n, \tag{247}$$

and therefore

$$N(^3\mathrm{He}) = (+1) + (+1) + (-1) = +1. \tag{248}$$

Helium-4 contains two protons and two neutrons,

$$^4\mathrm{He}: \quad p + p + n + n, \tag{249}$$

so that

$$\boxed{N(^4\mathrm{He}) = 0}. \tag{250}$$

Thus, a nucleus containing equal numbers of protons and neutrons can have a vanishing total N because its positive and negative N contributions cancel.

The nucleosynthesis chain begins with deuterium formation through [1, 17]

$$p + n \to d + \gamma, \tag{251}$$

which satisfies

$$(+1) + (-1) = 0 + 0. \tag{252}$$

A subsequent reaction,

$$d + p \to {}^3\mathrm{He} + \gamma, \tag{253}$$

gives

$$0 + (+1) = (+1) + 0. \tag{254}$$

The corresponding tritium-producing channel

$$d + d \to {}^3\mathrm{H} + p \tag{255}$$

satisfies

$$0 + 0 = (-1) + (+1), \tag{256}$$

while

$$d + d \to {}^3\mathrm{He} + n \tag{257}$$

gives

$$0 + 0 = (+1) + (-1). \tag{258}$$

Representative standard helium-4 formation channels include [17]

$${}^3\mathrm{H} + d \to {}^4\mathrm{He} + n, \tag{259}$$

which satisfies

$$(-1) + 0 = 0 + (-1), \tag{260}$$

and

$${}^3\mathrm{He} + d \to {}^4\mathrm{He} + p, \tag{261}$$

which gives

$$(+1) + 0 = 0 + (+1). \tag{262}$$

Thus, the constituent-level additivity of N is maintained as protons and neutrons are rearranged into nuclei during nucleosynthesis.

Taken together, stellar fusion, early-Universe weak conversion, weak freeze-out, and Big Bang nucleosynthesis provide macroscopic examples in which the distribution of N among particle species and composite states can change while the total additive N quantum number remains conserved.

5 Global N Symmetry and Its Mathematical Relation to $B - L$

The microscopic and macroscopic processes examined in the preceding sections exhibit a common additive N-conservation structure across weak transitions, hadronic processes, stellar fusion, and early-Universe proton–neutron conversion. We now examine the mathematical relation between the weak-isospin-based quantum number N and the conventional quantum numbers Q, B, and L, and then derive the corresponding global cosmological relations.

The fundamental species-level classification is defined by

$$N_f \equiv 2T_{3L}(f_L). \tag{263}$$

Exact additive N conservation and the global condition

$$N_{\mathrm{tot}} = 0 \tag{264}$$

constitute stronger hypotheses.

The relation

$$N = 2Q - (B - L) \tag{265}$$

is derived from the Standard Model electroweak quantum-number assignments for fermion species defined by their left-handed weak-doublet orientation. For charge-conserving transitions within this domain, electric-charge conservation gives

$$\Delta N = -\Delta(B - L), \tag{266}$$

whereas for an electrically neutral fermionic cosmological sector,

$$N_{\text{tot}}^{(f)} = -(B - L)_{\text{tot}}^{(f)}. \tag{267}$$

5.1 Derivation of $N = 2Q - (B - L)$ from $N = 2T_{3L}$

For the left-handed quark and lepton doublets of the Standard Model, the electroweak charge relation is

$$Q_f = T_{3L}(f_L) + \frac{Y_f}{2}, \tag{268}$$

where Y_f denotes the weak hypercharge. For these fermion doublets,

$$Y_f = B_f - L_f. \tag{269}$$

Therefore [1,7,9],

$$Q_f = T_{3L}(f_L) + \frac{B_f - L_f}{2}, \tag{270}$$

and hence

$$2T_{3L}(f_L) = 2Q_f - (B_f - L_f). \tag{271}$$

Using

$$N_f = 2T_{3L}(f_L), \tag{272}$$

one obtains

$$\boxed{N_f = 2Q_f - (B_f - L_f)}. \tag{273}$$

For compact notation, this relation will be written as

$$\boxed{N = 2Q - (B - L)}. \tag{274}$$

For the first-generation fermions, it gives

$$N(u) = N(\nu_e) = +1, \qquad N(d) = N(e^-) = -1, \tag{275}$$

in agreement with the weak-isospin-based classification introduced in Sec. 2.
Thus, the relation

$$N = 2Q - (B - L) \tag{276}$$

is an identity derived from the Standard Model electroweak quantum-number assignments for fermion species defined by their left-handed weak-doublet orientation. The fundamental species-level definition of the present classification remains

$$N_f = 2T_{3L}(f_L). \tag{277}$$

5.2 Exact N Conservation and the Consequent $B-L$ Constraint

For a transition between physical states, the derived relation gives

$$\Delta N = 2\Delta Q - \Delta(B-L). \tag{278}$$

For electric-charge-conserving processes,

$$\Delta Q = 0, \tag{279}$$

and therefore

$$\boxed{\Delta N = -\Delta(B-L)}. \tag{280}$$

The stronger exact additive-N hypothesis requires

$$\boxed{\Delta N = 0.} \tag{281}$$

In a continuous field-theoretic realization, exact conservation of the additive quantum number N is naturally associated with a continuous global $U(1)_N$ symmetry. Invariance of the action under the corresponding $U(1)_N$ transformation gives, by Noether's theorem, a conserved current j_N^μ satisfying

$$\partial_\mu j_N^\mu = 0, \tag{282}$$

and hence a conserved total charge

$$N_{\text{tot}} = \int d^3x\, j_N^0, \qquad \frac{dN_{\text{tot}}}{dt} = 0. \tag{283}$$

Therefore, if the Universe begins in a globally balanced state with

$$N_{\text{tot}}(t_i) = 0, \tag{284}$$

exact N conservation preserves this condition throughout subsequent N-conserving evolution,

$$N_{\text{tot}}(t) = 0. \tag{285}$$

Consequently,

$$\Delta(B-L) = 0 \qquad (\Delta Q = 0). \tag{286}$$

Thus, for charge-conserving processes,

$$\boxed{\Delta N = 0 \quad \Longleftrightarrow \quad \Delta(B-L) = 0} \qquad (\Delta Q = 0). \tag{287}$$

This condition does not require separate conservation of B and L. Processes satisfying

$$\Delta B = \Delta L \neq 0 \tag{288}$$

remain compatible with exact additive N conservation. This possibility will be relevant to the interspecies transitions considered later in Sec. 6.3.

Conversely, a confirmed charge-conserving process satisfying

$$\Delta(B - L) \neq 0 \tag{289}$$

would imply

$$\Delta N \neq 0, \tag{290}$$

and would therefore falsify exact additive N conservation.

The algebraic equivalence above shows that N conservation and $B-L$ conservation impose the same zero-change condition for charge-conserving processes. The species-level definition of the weak-isospin-based classification, however, remains

$$N_f = 2T_{3L}(f_L). \tag{291}$$

Within the Standard Model, electroweak sphaleron processes violate $B+L$ while preserving $B-L$ [2, 18]. Preservation of $B-L$ does not by itself require its global cosmological value to satisfy

$$(B-L)_{\text{tot}} = 0. \tag{292}$$

Accordingly,

$$(B-L)_{\text{tot}} = 0 \tag{293}$$

is not the unique cosmological value required by the Standard Model. Rather, it represents a particular cosmological case or initial-condition class among the possible values of the conserved global $B-L$ quantity. Conservation of $B-L$ can preserve an initially specified value, but does not by itself determine that the value must initially be zero.

5.3 Global N Symmetry in an Electrically Neutral Universe

The fermionic identity

$$N_f = 2Q_f - (B_f - L_f) \tag{294}$$

can be summed over the fermionic content of a cosmological state. Let $q_N(i)$ denote the N charge of species i, and let $\mathcal{N}_i$ denote its total population, with particle and antiparticle species included separately in the sum. Then

$$N^{(f)}_{\text{tot}} = \sum_i q_N(i)\mathcal{N}_i. \tag{295}$$

and the species-level identity gives

$$N^{(f)}_{\text{tot}} = 2Q^{(f)}_{\text{tot}} - (B-L)^{(f)}_{\text{tot}}. \tag{296}$$

For an electrically neutral fermionic cosmological sector,

$$Q^{(f)}_{\text{tot}} = 0, \tag{297}$$

so that

$$N_{\text{tot}}^{(f)} = -(B-L)_{\text{tot}}^{(f)}. \tag{298}$$

Consequently,

$$\boxed{N_{\text{tot}}^{(f)} = 0 \quad \Longleftrightarrow \quad (B-L)_{\text{tot}}^{(f)} = 0} \qquad (Q_{\text{tot}}^{(f)} = 0). \tag{299}$$

The global N-symmetry hypothesis therefore selects the $B-L=0$ branch within the electrically neutral fermionic sector in which the derived identity applies.

The logical direction is important. The present framework does not begin by assuming

$$(B-L)_{\text{tot}} = 0 \tag{300}$$

and then infer $N_{\text{tot}} = 0$. Rather, the particle–antiparticle classification is introduced through $N_f = 2T_{3L}(f_L)$, and the additional global symmetry condition, when restricted to the fermionic sector considered here,

$$\boxed{N_{\text{tot}}^{(f)} = 0} \tag{301}$$

implies

$$(B-L)_{\text{tot}}^{(f)} = 0 \tag{302}$$

under electric neutrality.

Although the relation $N = 2Q-(B-L)$ was derived above from the fermionic electroweak assignments, it can be extended consistently to the Standard Model bosonic sector used in the present framework. The Standard Model gauge bosons and Higgs field carry

$$B = L = 0, \tag{303}$$

so that the same additive relation reduces in the bosonic sector to

$$N = 2Q. \tag{304}$$

It therefore gives

$$N(W^+) = +2, \qquad N(W^-) = -2, \qquad N(Z) = N(\gamma) = N(g) = 0, \qquad N(h) = 0, \tag{305}$$

in agreement with the gauge- and Higgs-sector assignments obtained from the interaction-level N-balance in Sec. 3.

Consequently, when the fermionic and bosonic contributions are combined, the total additive quantum number satisfies

$$\boxed{N_{\text{tot}} = 2Q_{\text{tot}} - (B-L)_{\text{tot}}}. \tag{306}$$

For an electrically neutral cosmological state,

$$Q_{\text{tot}} = 0, \tag{307}$$

and therefore

$$N_{\text{tot}} = -(B-L)_{\text{tot}}. \tag{308}$$

Hence,

$$\boxed{N_{\rm tot} = 0 \quad \Longleftrightarrow \quad (B-L)_{\rm tot} = 0} \qquad (Q_{\rm tot} = 0). \tag{309}$$

As established in Sec. 5.2, exact additive N conservation preserves an initially vanishing total N. Thus, the global $N_{\rm tot} = 0$ condition considered here is not restricted to a single cosmological epoch, but is preserved throughout subsequent N-conserving evolution once realized in the initial globally balanced state.

5.4 The Neutron–Neutrino Relation in the Conventional $B - L = 0$ Branch

For comparison, consider the conventional cosmological branch satisfying

$$(B-L)_{\rm tot} = 0. \tag{310}$$

Electroweak sphaleron processes preserve this condition if it is realized initially and no subsequent $B-L$-violating interaction changes it [2, 18].

For the late-Universe fermionic inventory, define the net abundance differences

$$\Delta_p \equiv \mathcal{N}_p - \mathcal{N}_{\bar{p}}, \qquad \Delta_n \equiv \mathcal{N}_n - \mathcal{N}_{\bar{n}}, \tag{311}$$

and

$$\Delta_e \equiv \mathcal{N}_{e^-} - \mathcal{N}_{e^+}, \qquad \Delta_\nu \equiv \mathcal{N}_\nu - \mathcal{N}_{\bar{\nu}}, \tag{312}$$

where $\mathcal{N}_\nu$ and $\mathcal{N}_{\bar{\nu}}$ denote the total populations summed over the active-neutrino flavors included in the bookkeeping.

The condition $B - L = 0$ becomes

$$\Delta_p + \Delta_n - \Delta_e - \Delta_\nu = 0. \tag{313}$$

Because the Universe is electrically neutral, the net proton and electron abundances satisfy [19]

$$\Delta_p = \Delta_e. \tag{314}$$

The charged contributions therefore cancel, leaving

$$\boxed{\Delta_\nu = \Delta_n}. \tag{315}$$

Equivalently,

$$\boxed{\mathcal{N}_\nu - \mathcal{N}_{\bar{\nu}} = \mathcal{N}_n - \mathcal{N}_{\bar{n}}}. \tag{316}$$

In the present observable Universe,

$$\mathcal{N}_{\bar{n}} \ll \mathcal{N}_n \tag{317}$$

[1], and hence

$$\boxed{\mathcal{N}_\nu - \mathcal{N}_{\bar{\nu}} \simeq \mathcal{N}_n}. \tag{318}$$

Thus, within the conventional $B - L = 0$ branch, electric neutrality relates the net active-neutrino abundance to the cosmic neutron abundance.

5.5 The Neutron–Neutrino Relation from Global N Symmetry

The same relation follows directly from the global N-symmetry condition.

Within the additive extension of N to the Standard Model particle content established above, the global condition is

$$N_{\text{tot}} = 0. \tag{319}$$

For the late-Universe particle inventory relevant to the present abundance relation, the macroscopic nonzero N contributions are carried by the residual proton, neutron, electron, and neutrino sectors. Their assignments are

$$N(p) = +1, \qquad N(n) = -1, \qquad N(e^-) = -1, \qquad N(\nu) = +1. \tag{320}$$

Using the abundance differences defined in Sec. 5.4, the total additive N can therefore be written as

$$N_{\text{tot}} = \Delta_p - \Delta_n - \Delta_e + \Delta_\nu. \tag{321}$$

Global N symmetry then requires

$$\boxed{N_{\text{tot}} = \Delta_p - \Delta_n - \Delta_e + \Delta_\nu = 0}. \tag{322}$$

Electric neutrality again gives

$$\Delta_p = \Delta_e, \tag{323}$$

so that

$$-\Delta_n + \Delta_\nu = 0. \tag{324}$$

Therefore,

$$\boxed{\Delta_\nu = \Delta_n}, \tag{325}$$

or equivalently,

$$\boxed{\mathcal{N}_\nu - \mathcal{N}_{\bar{\nu}} = \mathcal{N}_n - \mathcal{N}_{\bar{n}}}. \tag{326}$$

Observations of the present observable Universe indicate that the antineutron abundance is negligible compared with the neutron abundance [1],

$$\mathcal{N}_{\bar{n}} \ll \mathcal{N}_n. \tag{327}$$

Therefore,

$$\boxed{\mathcal{N}_\nu - \mathcal{N}_{\bar{\nu}} \simeq \mathcal{N}_n}. \tag{328}$$

Thus, the conventional $B - L = 0$ derivation in Sec. 5.4 and the global N-symmetry derivation yield the same mathematical neutron–neutrino relation.

This agreement follows from the global relation

$$N_{\text{tot}} = -(B - L)_{\text{tot}} \tag{329}$$

under electric neutrality.

The two formulations nevertheless differ in their physical starting point. The conventional derivation begins by selecting the $B-L=0$ case, whereas the present framework begins from the weak-isospin-based classification and imposes the global condition

$$N_{\text{tot}} = 0. \tag{330}$$

Moreover, $B-L=0$ is not a unique cosmological condition fixed by the Standard Model. Conservation of $B-L$ preserves a given global $B-L$ value but does not require that value to vanish. Cosmological cases with

$$(B-L)_{\text{tot}} \neq 0 \tag{331}$$

are therefore also possible under $B-L$ conservation [2]. Beyond the Standard Model, interactions that violate lepton number and consequently $B-L$ can also occur [20].

5.6 The Same Mathematical Relation and a Different Physical Interpretation

The conventional Standard Model particle–antiparticle nomenclature and the weak-isospin-based classification organize the same physical fermionic populations differently across species.

In the conventional classification, the observed excess populations of protons, neutrons, and electrons belong to the conventional matter sector. Within the $B-L=0$ case considered above, the relation

$$\Delta_\nu = \Delta_n > 0 \tag{332}$$

predicts a positive neutrino–antineutrino abundance difference. The net excess components are therefore conventionally represented by

$$p, \qquad n, \qquad e^-, \qquad \nu. \tag{333}$$

The weak-isospin-based classification reorganizes these same components according to

$$p, \nu \quad : \quad N > 0, \tag{334}$$

and

$$e^-, n \quad : \quad N < 0. \tag{335}$$

Electric neutrality gives

$$\Delta_p = \Delta_e, \tag{336}$$

so the net positive N contribution of the proton sector is canceled by the net negative N contribution of the electron sector. Likewise,

$$\Delta_\nu = \Delta_n \tag{337}$$

ensures cancellation between the positive N contribution of the neutrino sector and the negative N contribution of the neutron sector.

Consequently,

$$N_{\text{tot}} = 0. \tag{338}$$

Thus, the same fermionic population that appears strongly particle dominated under the conventional classification is organized into globally canceling positive-N and negative-N sectors under the weak-isospin-based classification.

Importantly, the global condition $N_{\text{tot}} = 0$ does not require the abundance difference of each charge-conjugate pair to vanish separately. Nor does it determine why the realized Universe selects a particular sign for the proton–antiproton, neutron–antineutron, electron–positron, or neutrino–antineutrino abundance differences. The global symmetry problem and the species-level abundance-orientation problem are therefore distinct. The latter is examined in Sec. 6, where a possible N-conserving microscopic mechanism for correlated species-level asymmetry generation is developed.

6 A Weak-Isospin-Based Resolution Framework for the Particle–Antiparticle and Baryon Asymmetry Problems

6.1 From an Early Particle–Antiparticle Symmetric State to the Present Species-Level Asymmetries

The particle–antiparticle and baryon asymmetry problems can be stated most directly by comparing an early particle–antiparticle symmetric state with the realized species-level abundance pattern of the present Universe.

Particle–antiparticle pair production and annihilation are well-established physical processes. For example, a pair-production reaction of the form

$$\gamma + \gamma \longleftrightarrow f + \bar{f} \tag{339}$$

creates a particle and its charge-conjugate partner together. At the level of the pair-production process itself,

$$\delta n_f^{\text{pair}} = \delta n_{\bar{f}}^{\text{pair}}. \tag{340}$$

Likewise, pair annihilation removes the particle and antiparticle together. More generally, high-energy radiation and thermal interactions can produce and annihilate particle–antiparticle pairs while preserving the relevant conserved quantum numbers [1,7].

In the absence of a pre-existing particle–antiparticle asymmetry and before any dynamics selecting a preferred abundance orientation has acted, the corresponding early-Universe reference state is particle–antiparticle symmetric. For a given species, equal particle and antiparticle abundances provide a natural and commonly considered reference initial condition in early-Universe cosmology.

$$n_f = n_{\bar{f}}. \tag{341}$$

Equivalently,

$$\Delta_f \equiv n_f - n_{\bar{f}} = 0. \tag{342}$$

At temperatures above hadronization, this symmetry is most naturally expressed in terms of quarks, antiquarks, leptons, and antileptons. For example,

$$n_q = n_{\bar{q}}. \tag{343}$$

After hadronization, if no species-level asymmetry-generating dynamics had yet selected a preferred orientation, the corresponding symmetric hadronic and leptonic state can be represented schematically by

$$n_p = n_{\bar{p}}, \qquad n_n = n_{\bar{n}}, \tag{344}$$

and

$$n_{e^-} = n_{e^+}, \qquad n_{\nu_\alpha} = n_{\bar{\nu}_\alpha}. \tag{345}$$

To describe the subsequent species-level abundances, define

$$\Delta_p \equiv n_p - n_{\bar{p}}, \qquad \Delta_n \equiv n_n - n_{\bar{n}}, \tag{346}$$

and

$$\Delta_e \equiv n_{e^-} - n_{e^+}, \qquad \Delta_\nu \equiv \sum_{\alpha=e,\mu,\tau} \left(n_{\nu_\alpha} - n_{\bar{\nu}_\alpha}\right). \tag{347}$$

The initial symmetric reference state is therefore

$$\boxed{\Delta_p = \Delta_n = \Delta_e = \Delta_\nu = 0}. \tag{348}$$

However, the present cosmic abundance pattern is different. The observed Universe contains positive net proton, neutron, and electron abundances,

$$\boxed{\Delta_p > 0, \qquad \Delta_n > 0, \qquad \Delta_e > 0}. \tag{349}$$

The positive proton and neutron abundance differences follow from the macroscopic dominance of ordinary nucleons over antinucleons, while cosmic electric neutrality relates the net electron abundance to the net proton abundance [1,19].

For the neutrino sector, the sign of the cosmic neutrino–antineutrino asymmetry has not yet been directly established observationally. Within the global N-symmetry framework developed in Sec. 5, however,

$$\Delta_\nu = \Delta_n. \tag{350}$$

Since the observed neutron abundance orientation satisfies

$$\Delta_n > 0, \tag{351}$$

the framework predicts

$$\boxed{\Delta_\nu > 0}. \tag{352}$$

The same conditional relation follows from conventional $B-L$ bookkeeping within the electrically neutral $B-L=0$ cosmological case. Electric neutrality gives $\Delta_p = \Delta_e$, while $(B-L)_{\text{tot}} = 0$ then gives

$$\Delta_\nu = \Delta_n > 0. \tag{353}$$

Thus, a positive neutrino–antineutrino asymmetry is not presently an observed fact. However, it is a theoretically derived and observationally testable relation that follows from global N symmetry in the present framework and, conditionally, from the conventional $B-L=0$ cosmological case.

Accordingly, when the observational results and the theoretical relations derived above are considered together, the present abundance orientation can be summarized as

$$\Delta_p > 0, \qquad \Delta_n > 0, \qquad \Delta_e > 0, \qquad \Delta_\nu > 0. \tag{354}$$

The first three signs correspond to the observed macroscopic matter composition of the Universe, whereas the fourth is a theoretical prediction derived from the global conditions described above.

The species-level particle–antiparticle asymmetry problem can therefore be formulated as the dynamical evolution from the initial symmetric reference state,

$$\boxed{\Delta_p = \Delta_n = \Delta_e = \Delta_\nu = 0}, \tag{355}$$

to the realized correlated abundance orientation,

$$\boxed{\Delta_p > 0, \qquad \Delta_n > 0, \qquad \Delta_e > 0, \qquad \Delta_\nu > 0}. \tag{356}$$

In the conventional Standard Model particle–antiparticle classification, the baryonic part of this question corresponds to the familiar baryon–antibaryon asymmetry problem [1–3]. If baryons and antibaryons originated from an initially symmetric population, what physical dynamics generated the surviving excess of baryons over antibaryons?

The baryon asymmetry problem is also often discussed as part of the broader particle–antiparticle asymmetry problem or matter–antimatter asymmetry problem.

More generally, the particle–antiparticle asymmetry problem considered here can be stated as

$$\boxed{\begin{array}{c}\text{What physical dynamics transformed an initially particle–antiparticle}\\ \text{symmetric state into the realized correlated species-level abundance}\\ \text{orientations?}\end{array}} \tag{357}$$

6.2 Two-Level Structure of the Particle–Antiparticle Asymmetry Problem

The comparison developed in Sec. 6.1 separates the particle–antiparticle asymmetry problem into two conceptually distinct levels. The first concerns the global balance between positive-N and negative-N sectors. The second concerns the realized abundance orientation of individual charge-conjugate species.

Using the species-level abundance differences defined in Sec. 6.1, the late-Universe particle inventory relevant to the present abundance relation has its macroscopic nonzero N contributions in the proton, neutron, electron, and neutrino sectors. The total additive N can therefore be written as

$$\boxed{N_{\text{tot}} = \Delta_p - \Delta_n - \Delta_e + \Delta_\nu}. \tag{358}$$

This relation provides the basis for distinguishing the global and species-level problems.

6.2.1 Global Particle–Antiparticle Asymmetry

The first level is the *global particle–antiparticle asymmetry problem*.

The particle–antiparticle symmetric reference state introduced in Sec. 6.1 satisfies

$$N_{\text{tot}} = 0. \tag{359}$$

If the additive quantum number N is conserved, $\Delta N_{\text{tot}} = 0$, then an initially vanishing total N remains zero throughout subsequent N-conserving evolution:

$$N_{\text{tot}}^{\text{initial}} = 0 \quad \Longrightarrow \quad N_{\text{tot}}^{\text{final}} = 0. \tag{360}$$

Within the stronger global-N hypothesis developed in this work,

$$\boxed{N_{\text{tot}} = 0} \tag{361}$$

is identified with global particle–antiparticle symmetry in the weak-isospin-based classification.

Importantly, this global condition does not require equality within every individual charge-conjugate pair. In particular,

$$N_{\text{tot}} = 0 \tag{362}$$

does not imply

$$\Delta_p = \Delta_n = \Delta_e = \Delta_\nu = 0. \tag{363}$$

A cosmological state can therefore contain nonzero species-level abundance differences while remaining globally balanced between positive-N and negative-N sectors.

The global relations derived in Sec. 5 make this structure explicit. Electric neutrality gives

$$\boxed{\Delta_p = \Delta_e}, \tag{364}$$

while global N symmetry gives

$$\boxed{\Delta_\nu = \Delta_n}. \tag{365}$$

Hence,

$$N_{\text{tot}} = (\Delta_p - \Delta_e) + (\Delta_\nu - \Delta_n) = 0. \tag{366}$$

Thus, the simultaneous abundance orientations

$$\boxed{\Delta_p > 0, \qquad \Delta_n > 0, \qquad \Delta_e > 0, \qquad \Delta_\nu > 0} \tag{367}$$

are fully compatible with

$$\boxed{N_{\text{tot}} = 0}. \tag{368}$$

The first three signs correspond to the observed macroscopic matter composition discussed in Sec. 6.1, whereas the positive neutrino–antineutrino asymmetry is a theoretical prediction under the global conditions derived in Sec. 5.

Thus, the fermionic population that appears strongly particle dominated under the conventional classification is reorganized, in the weak-isospin-based classification, into mutually canceling positive-N and negative-N sectors.

Accordingly, within the global-N hypothesis, the global particle–antiparticle asymmetry problem is resolved at the level of the signed total N balance:

$$\boxed{\text{global particle–antiparticle symmetry} \quad \Longleftrightarrow \quad N_{\text{tot}} = 0}. \tag{369}$$

6.2.2 Species-Level Particle–Antiparticle Asymmetry and a Structural Clue from the Weak-Isospin Classification

The second level is the *species-level particle–antiparticle asymmetry problem*.

Although the global condition $N_{\rm tot} = 0$ can be maintained, it does not determine which member of an individual charge-conjugate pair becomes more abundant. For example, global N symmetry alone does not determine why $n_p > n_{\bar{p}}$ is realized rather than $n_{\bar{p}} > n_p$.

The same abundance-orientation question applies to

$$n_n \text{ vs. } n_{\bar{n}}, \qquad n_{e^-} \text{ vs. } n_{e^+}, \qquad n_{\nu_\alpha} \text{ vs. } n_{\bar{\nu}_\alpha}, \tag{370}$$

and more generally to other charge-conjugate species.

The conventional baryon–antibaryon asymmetry problem is therefore a baryonic realization of this more general species-level particle–antiparticle abundance-orientation problem. The same statement applies to lepton–antilepton and other species-specific abundance asymmetries.

The weak-isospin-based classification nevertheless provides an important structural clue.

For the principal fermionic species,

$$N(p) = +1, \qquad N(n) = -1, \qquad N(e^-) = -1, \qquad N(\nu) = +1. \tag{371}$$

Consequently, species-level abundance excesses having the same conventional orientation do not contribute with the same sign to the global N balance. The proton and neutrino excesses contribute positively, whereas the neutron and electron excesses contribute negatively.

The presently relevant abundance orientation,

$$\boxed{\Delta_p > 0, \qquad \Delta_n > 0, \qquad \Delta_e > 0, \qquad \Delta_\nu > 0}, \tag{372}$$

can therefore satisfy

$$\boxed{N_{\rm tot} = 0} \tag{373}$$

through the relations

$$\Delta_p = \Delta_e, \qquad \Delta_\nu = \Delta_n. \tag{374}$$

Equivalently,

$$N_{\rm tot} = (\Delta_p - \Delta_e) + (\Delta_\nu - \Delta_n) = 0. \tag{375}$$

This structure shows that generating nonzero species-level asymmetries does not require the generation of a nonzero global particle–antiparticle charge. Instead, several species-level abundance differences can develop in a correlated manner while their signed N contributions continue to cancel globally.

It is therefore possible that the proton, neutron, electron, and neutrino abundance orientations are not generated by four independent microscopic mechanisms. They may instead arise from a common N-conserving dynamics that changes several species-level abundance differences simultaneously.

A mechanism that explains the origin of the particle–antiparticle asymmetry must begin from an initially symmetric state,

$$\Delta_p = \Delta_n = \Delta_e = \Delta_\nu = 0, \tag{376}$$

and generate the present abundance orientations indicated by observation and the theoretical relation derived above,

$$\boxed{\Delta_p > 0, \qquad \Delta_n > 0, \qquad \Delta_e > 0, \qquad \Delta_\nu > 0}. \tag{377}$$

The two levels of the asymmetry problem can therefore be summarized as

Table 4: Two-level classification of the particle–antiparticle asymmetry problem in the weak-isospin-based framework.

Asymmetry problem	**Weak-isospin-based N framework**
Global particle–antiparticle asymmetry	Within the global-N hypothesis, the initial particle–antiparticle symmetric condition and additive N conservation preserve the global balance $N_{\mathrm{tot}} = 0$, even when individual species-level abundance differences are nonzero.
Species-level particle–antiparticle asymmetry	Remains a particle physics problem of abundance-orientation selection. Global N symmetry alone does not determine which member of each charge-conjugate pair becomes more abundant, but the N structure permits several species-level asymmetries to arise through a common N-conserving dynamics.

6.3 A Possible N-Conserving Mechanism for Species-Level Asymmetry Generation

The preceding analysis showed that the four abundance orientations

$$\Delta_p > 0, \qquad \Delta_n > 0, \qquad \Delta_e > 0, \qquad \Delta_\nu > 0 \tag{378}$$

can coexist with the exact global condition

$$N_{\mathrm{tot}} = 0. \tag{379}$$

This structure raises the possibility that the four species-level asymmetries need not originate from four independent mechanisms. Instead, a common microscopic dynamics conserving the total additive N quantum number may generate several correlated abundance orientations simultaneously.

In this section, we examine a representative class of transitions that realizes this possibility.

6.3.1 Simultaneous Generation of Four Species-Level Asymmetries

Consider the hypothetical transition

$$\boxed{\bar{n} \to p + e^- + \nu_e}. \tag{380}$$

This process is not claimed here to be an experimentally established antineutron decay channel. Rather, it is considered as a representative candidate transition illustrating how the species-level particle–antiparticle asymmetry problem may be addressed within an N-conserving framework.

The $|\Delta B| = 2$ decay channels considered here are absent from the renormalizable Standard Model, but they can arise from baryon-number-violating interactions beyond the Standard Model [1, 21].

For the particular N-conserving channel considered in the present framework,

$$n \to \bar{p} + e^+ + \bar{\nu}_e, \tag{381}$$

the additive N balance is

$$N(n) = -1, \qquad N(\bar{p}) + N(e^+) + N(\bar{\nu}_e) = (-1) + (+1) + (-1) = -1, \tag{382}$$

and therefore

$$\Delta N = 0. \tag{383}$$

In terms of the conventional baryon and lepton numbers, the same process

$$n \to \bar{p} + e^+ + \bar{\nu}_e \tag{384}$$

satisfies

$$\Delta B = \Delta L = -2, \qquad \Delta(B - L) = 0. \tag{385}$$

The same process has a different interpretation under the weak-isospin-based N classification. To distinguish this interpretation from the conventional Standard Model baryon and lepton numbers, let B_N and L_N denote the baryonic and leptonic orientation numbers defined by the sign of N.

In the baryonic sector, both the neutron and the antiproton belong to the negative-N antibaryon sector,

$$B_N(n) = -1, \qquad B_N(\bar{p}) = -1, \tag{386}$$

so that

$$\Delta B_N = 0. \tag{387}$$

In the leptonic sector, the positron belongs to the positive-N lepton sector, whereas the antineutrino belongs to the negative-N antilepton sector,

$$L_N(e^+) = +1, \qquad L_N(\bar{\nu}_e) = -1. \tag{388}$$

Their contributions cancel,

$$L_{N,\mathrm{final}} = L_N(e^+) + L_N(\bar{\nu}_e) = (+1) + (-1) = 0, \tag{389}$$

and therefore

$$\Delta L_N = 0. \tag{390}$$

Thus, the same physical decay is described in the **conventional Standard Model baryon- and lepton-number bookkeeping** as

$$\boxed{\Delta B = \Delta L = -2}, \tag{391}$$

whereas, in the **weak-isospin-based classification**, it preserves the corresponding baryonic and leptonic orientation numbers,

$$\boxed{\Delta B_N = \Delta L_N = 0}. \tag{392}$$

At the same time, the total additive N is conserved,

$$N(n) = N(\bar{p}) + N(e^+) + N(\bar{\nu}_e), \tag{393}$$

or explicitly,

$$-1 = (-1) + (+1) + (-1), \tag{394}$$

so that

$$\Delta N = 0. \tag{395}$$

Thus, this channel is absent in the renormalizable Standard Model but is allowed within the additive N-conserving framework proposed here. Observation of such a decay would demonstrate physics beyond the renormalizable Standard Model and would provide empirical support for the possibility that the weak-isospin-based N classification captures a conserved structure underlying particle conversions that is not manifest in the conventional baryon- and lepton-number assignments.

For the relevant particles,

$$N(\bar{n}) = +1, \qquad N(p) = +1, \qquad N(e^-) = -1, \qquad N(\nu_e) = +1. \tag{396}$$

The initial and final N values are therefore

$$N_{\text{initial}} = +1, \tag{397}$$

and

$$N_{\text{final}} = (+1) + (-1) + (+1) = +1, \tag{398}$$

so that

$$\boxed{\Delta N = 0}. \tag{399}$$

Electric charge is also conserved,

$$Q_{\text{initial}} = 0, \tag{400}$$

and

$$Q_{\text{final}} = (+1) + (-1) + 0 = 0, \tag{401}$$

which gives

$$\boxed{\Delta Q = 0}. \tag{402}$$

In terms of the conventional baryon and lepton numbers, the transition changes

$$B: \quad -1 \to +1, \tag{403}$$

and therefore

$$\boxed{\Delta B = +2}. \tag{404}$$

Likewise,

$$L: \quad 0 \to +2, \tag{405}$$

so that

$$\boxed{\Delta L = +2}. \tag{406}$$

Consequently,

$$\boxed{\Delta(B-L) = 0}. \tag{407}$$

Thus, baryon number and lepton number are individually changed, while their difference is preserved,

$$\Delta B = \Delta L. \tag{408}$$

This is consistent with

$$N = 2Q - (B-L) \tag{409}$$

when both N and electric charge are conserved.
The more significant feature appears at the species level. Define

$$\Delta_p = n_p - n_{\bar{p}}, \qquad \Delta_n = n_n - n_{\bar{n}}, \tag{410}$$

and

$$\Delta_e = n_{e^-} - n_{e^+}, \qquad \Delta_\nu = n_{\nu_e} - n_{\bar{\nu}_e} \tag{411}$$

for the present elementary transition.
A single

$$\bar{n} \to p + e^- + \nu_e \tag{412}$$

event creates one proton and therefore gives

$$\delta\Delta_p = +1. \tag{413}$$

It simultaneously removes one antineutron, giving

$$\delta\Delta_n = +1. \tag{414}$$

Although no neutron is directly produced, the decrease of $n_{\bar{n}}$ increases

$$\Delta_n = n_n - n_{\bar{n}} \tag{415}$$

by one unit.
The production of one electron and one electron neutrino similarly gives

$$\delta\Delta_e = +1, \qquad \delta\Delta_\nu = +1. \tag{416}$$

Therefore, one microscopic transition produces

$$\boxed{\left(\delta\Delta_p, \delta\Delta_n, \delta\Delta_e, \delta\Delta_\nu\right) = (+1, +1, +1, +1)}. \tag{417}$$

The transition therefore changes the proton–antiproton, neutron–antineutron, electron–positron, and neutrino–antineutrino abundance differences simultaneously in the same positive direction.

At the same time, it satisfies

$$\boxed{\Delta N = 0, \qquad \Delta Q = 0, \qquad \Delta(B-L) = 0}, \tag{418}$$

while allowing

$$\boxed{\Delta B = \Delta L = +2}. \tag{419}$$

This provides an explicit theoretical example in which four correlated species-level asymmetries can be generated without producing a global N asymmetry.

6.3.2 CP-Conjugate Transition and Selection of the Abundance Orientation

The CP-conjugate transition is

$$\boxed{n \to \bar{p} + e^{+} + \bar{\nu}_e}. \tag{420}$$

A single occurrence of this process produces the opposite species-level change,

$$\boxed{\left(\delta\Delta_p, \delta\Delta_n, \delta\Delta_e, \delta\Delta_\nu\right) = (-1, -1, -1, -1)}. \tag{421}$$

If the two CP-conjugate processes occurred with exactly equal effective rates in a symmetric initial state, their contributions would cancel and no net species-level abundance orientation would be generated.

Define the corresponding partial rates by

$$\Gamma_+ \equiv \Gamma\left(\bar{n} \to p + e^{-} + \nu_e\right), \tag{422}$$

and

$$\Gamma_- \equiv \Gamma\left(n \to \bar{p} + e^{+} + \bar{\nu}_e\right). \tag{423}$$

For general neutron and antineutron number densities, the direct source contribution to the four abundance differences has the schematic form

$$\frac{d}{dt}\begin{pmatrix}\Delta_p\\ \Delta_n\\ \Delta_e\\ \Delta_\nu\end{pmatrix}\Bigg|_{\text{source}} = \left(n_{\bar{n}}\Gamma_+ - n_n\Gamma_-\right)\begin{pmatrix}1\\1\\1\\1\end{pmatrix} + \cdots, \tag{424}$$

where the ellipsis denotes inverse reactions, washout effects, and other terms required in a complete kinetic description.

For a symmetric initial state,

$$n_{\bar{n}} = n_n \equiv n_0, \tag{425}$$

the direct source term reduces to

$$\frac{d}{dt}\begin{pmatrix}\Delta_p\\ \Delta_n\\ \Delta_e\\ \Delta_\nu\end{pmatrix}\Bigg|_{\text{source}} = n_0\left(\Gamma_+ - \Gamma_-\right)\begin{pmatrix}1\\1\\1\\1\end{pmatrix} + \cdots. \tag{426}$$

A net positive orientation of the four abundance differences therefore requires, for this symmetric initial condition,

$$\boxed{\Gamma_+ > \Gamma_-}. \tag{427}$$

A convenient partial-rate asymmetry parameter may be defined as

$$\epsilon_N = \frac{\Gamma_+ - \Gamma_-}{\Gamma_+ + \Gamma_-}. \tag{428}$$

Thus,

$$\epsilon_N > 0 \tag{429}$$

corresponds to a positive direct source orientation for the four abundance differences in the symmetric initial state.

In a full cosmological treatment, the number-density evolution would be described by Boltzmann equations containing Hubble dilution, inverse reactions, and washout terms in addition to the direct source contribution shown above.

Thus, a single CP-asymmetric microscopic dynamics can, in principle, select the same abundance orientation for all four species rather than requiring four independent asymmetry-generating mechanisms.

If CPT symmetry is preserved, the total decay widths of the neutron and antineutron must be equal [1]. The mechanism considered here therefore does not require a difference between their total lifetimes. What is required is a CP asymmetry in specific partial channels, such as

$$\boxed{\Gamma\left(\bar{n} \to p + e^- + \nu_e\right) \neq \Gamma\left(n \to \bar{p} + e^+ + \bar{\nu}_e\right)}. \tag{430}$$

Any such partial-rate asymmetry must be embedded consistently within the complete set of available channels.

In addition, a persistent cosmological asymmetry requires that inverse reactions and washout processes do not restore complete equilibrium.

The minimal dynamical structure is therefore characterized by

$$\boxed{\Delta N = 0, \qquad \Delta(B-L) = 0, \qquad \Delta B = \Delta L \neq 0}, \tag{431}$$

together with CP-asymmetric dynamics and departure from thermal equilibrium [2,3].

For comparison, the same weak-isospin-based analysis can be applied to the standard neutron beta decay and its charge-conjugate decay. The standard beta decay

$$n \to p + e^- + \bar{\nu}_e \tag{432}$$

produces the species-level change

$$\boxed{\left(\delta\Delta_p, \delta\Delta_n, \delta\Delta_e, \delta\Delta_\nu\right) = (+1, -1, +1, -1)}. \tag{433}$$

It therefore drives the abundance differences in the directions

$$\Delta_p > 0, \qquad \Delta_n < 0, \qquad \Delta_e > 0, \qquad \Delta_\nu < 0. \tag{434}$$

Its charge-conjugate decay,

$$\bar{n} \to \bar{p} + e^+ + \nu_e, \tag{435}$$

produces the opposite species-level change,

$$\boxed{\left(\delta\Delta_p, \delta\Delta_n, \delta\Delta_e, \delta\Delta_\nu\right) = (-1, +1, -1, +1)}, \tag{436}$$

corresponding to

$$\Delta_p < 0, \qquad \Delta_n > 0, \qquad \Delta_e < 0, \qquad \Delta_\nu > 0. \tag{437}$$

Both standard beta-decay channels conserve the additive N quantum number. Their species-level asymmetry vectors are exactly opposite, so equal effective decay rates in a symmetric neutron–antineutron population would produce no net abundance orientation. If the two effective beta-decay rates were different in a symmetric neutron–antineutron population, the two opposite species-level changes would not cancel completely, and a net abundance orientation could be generated. However, the asymmetry direction produced by this beta-decay family,

$$(+1, -1, +1, -1), \tag{438}$$

or its opposite, does not reproduce the correlated abundance direction

$$(+1, +1, +1, +1) \tag{439}$$

required to account for the present cosmic abundance pattern. It is therefore not the primary asymmetry-generating process considered here. Nevertheless, a direct experimental comparison of the neutron and antineutron beta-decay rates would be worthwhile.

6.3.3 N-Conserving Four-Species Asymmetry Transition Family

The structure described above is not restricted to the single decay form

$$\bar{n} \to p + e^- + \nu_e. \tag{440}$$

Related crossed channels associated with the same underlying interaction structure can be written by crossing external particles between the initial and final states [7].

For example, crossing the electron to the initial state gives

$$\boxed{\bar{n} + e^+ \to p + \nu_e}. \tag{441}$$

In this process, one antineutron and one positron are removed, while one proton and one neutrino are produced. Therefore,

$$\boxed{\left(\delta\Delta_p, \delta\Delta_n, \delta\Delta_e, \delta\Delta_\nu\right) = (+1, +1, +1, +1)}. \tag{442}$$

Crossing the neutrino instead gives

$$\boxed{\bar{n} + \bar{\nu}_e \to p + e^-}. \tag{443}$$

Here, the removal of one antineutron and one antineutrino, together with the production of one proton and one electron, again yields

$$\boxed{\left(\delta\Delta_p, \delta\Delta_n, \delta\Delta_e, \delta\Delta_\nu\right) = (+1, +1, +1, +1)}. \tag{444}$$

Crossing the proton gives another related channel,

$$\boxed{\bar{n} + \bar{p} \to e^- + \nu_e}, \tag{445}$$

which removes one antineutron and one antiproton and produces one electron and one neutrino. It therefore produces the same four-species asymmetry vector.

Additional higher-multiplicity crossed channels can also be written, for example,

$$\bar{n} + e^+ + \bar{\nu}_e \to p, \tag{446}$$

although reactions requiring several particles to meet simultaneously are generally expected to be less important in dilute environments than one-body decays or two-body collisions.

An analogous proton-sector family may also be considered. For example,

$$\bar{p} \to n + e^- + \nu_e \tag{447}$$

has the same species-level asymmetry structure, although the free decay is not kinematically allowed because the final-state rest mass exceeds the antiproton mass [1].

With sufficient center-of-mass energy, related scattering processes such as

$$\boxed{\bar{p} + e^+ \to n + \nu_e} \tag{448}$$

and

$$\boxed{\bar{p} + \bar{\nu}_e \to n + e^-} \tag{449}$$

can be considered.

Each of these scattering processes, if dynamically allowed, produces

$$\boxed{\left(\delta\Delta_p, \delta\Delta_n, \delta\Delta_e, \delta\Delta_\nu\right) = (+1, +1, +1, +1)}. \tag{450}$$

In particular, under the high-density conditions of the early Universe, such $2 \to 2$ collision processes may, depending on the underlying interaction strength and kinematic accessibility, have played a more important role than the corresponding $1 \to 3$ spontaneous decay channels. Since the reaction rate per incident particle for a $2 \to 2$ process scales schematically as

$$\Gamma_{\text{coll}} \sim n_{\text{target}} \langle \sigma v \rangle, \tag{451}$$

the rates of kinematically allowed collision channels could have been substantially enhanced in the hot and dense early Universe, where positrons, neutrinos, and antineutrinos were abundant [1, 17]. Therefore, the cosmological relevance of this transition family should be evaluated by considering both the $1 \to 3$ spontaneous decays and the corresponding $2 \to 2$ scattering channels.

The detailed importance of each channel depends on its kinematic accessibility, particle densities, interaction strength, and the underlying microscopic operator. The purpose of the examples above is therefore not to assert that all such channels operated with comparable efficiency in the early Universe, but to identify a common transition structure capable of producing the required correlated abundance orientations.

More general processes involving additional photons, gauge bosons, scalar fields, or other particles may enlarge this transition family further.

Accordingly,

$$\bar{n} \to p + e^- + \nu_e \tag{452}$$

should be regarded not as the unique reaction capable of generating the four species-level asymmetries, but as one of the simplest representative transitions. Through crossing and related realizations, it belongs to a broader class of processes sharing the same species-level asymmetry vector,

$$(+1,+1,+1,+1). \tag{453}$$

6.3.4 Theoretical Status of the Proposed Mechanism

The N-conserving transitions proposed in this section, where N-conservation refers to conservation of the total additive N quantum number, provide a possible particle physics mechanism for the species-level particle–antiparticle asymmetry problem.

We do not claim that these processes have already been experimentally established as the origin of the cosmological asymmetries. The proposal is instead that, if such N-conserving transitions operated in the early Universe and their CP-conjugate decay channels had different partial decay rates or their CP-conjugate scattering channels had different cross sections, they could simultaneously generate, through a common interspecies transition process, the observed proton, neutron, and electron abundance orientations together with the positive neutrino asymmetry predicted by the present framework.

For example, if

$$\Gamma\left(\bar{n} \to p + e^- + \nu_e\right) > \Gamma\left(n \to \bar{p} + e^+ + \bar{\nu}_e\right), \tag{454}$$

the net effect drives

$$\boxed{\delta\Delta_p^{\text{net}} = \delta\Delta_n^{\text{net}} = \delta\Delta_e^{\text{net}} = \delta\Delta_\nu^{\text{net}} > 0}. \tag{455}$$

An important feature of this mechanism is that the asymmetry need not originate directly from asymmetric pair production within a single particle–antiparticle species. A symmetric pair-production process, for example

$$X \to p + \bar{p}, \tag{456}$$

does not itself generate a proton–antiproton asymmetry. However, subsequent interspecies decays and conversion reactions can transform the initially produced particles and antiparticles into different species with unequal final abundances while preserving the global N balance.

The transition

$$\bar{n} \to p + e^- + \nu_e \tag{457}$$

provides an explicit realization of this possibility. A single event removes one antineutron while producing one proton, one electron, and one neutrino, giving

$$\boxed{\left(\delta\Delta_p, \delta\Delta_n, \delta\Delta_e, \delta\Delta_\nu\right) = (+1,+1,+1,+1)}. \tag{458}$$

At the same time,

$$\boxed{\Delta N = 0, \qquad \Delta Q = 0, \qquad \Delta(B-L) = 0}, \tag{459}$$

while

$$\boxed{\Delta B = \Delta L = +2}. \tag{460}$$

We therefore propose this class of N-conserving interspecies transitions as a possible solution to the species-level particle–antiparticle asymmetry problem. The direct experimental questions are whether such channels exist and whether their CP-conjugate partial decay rates or scattering cross sections exhibit a nonzero asymmetry.

More generally, the species-level particle–antiparticle asymmetry problem need not require the generation of a nonzero global N asymmetry. Species-dependent decay and conversion processes may select correlated abundance orientations while maintaining

$$\boxed{N_{\mathrm{tot}} = 0}. \tag{461}$$

6.3.5 Quark-Level Asymmetry and the Net u- and d-Quark Abundances

The interspecies transition mechanism discussed above also has a direct interpretation at the quark level.

Before hadronization, the particle–antiparticle symmetric initial condition of Sec. 6.1 may be written for the light quark flavors as

$$n_u = n_{\bar{u}}, \qquad n_d = n_{\bar{d}}, \tag{462}$$

or equivalently,

$$\Delta_u \equiv n_u - n_{\bar{u}} = 0, \qquad \Delta_d \equiv n_d - n_{\bar{d}} = 0. \tag{463}$$

After hadronization, quarks and antiquarks are confined into hadrons. The principal nucleon and antinucleon valence-quark contents are [1]

$$p = (uud), \qquad n = (udd), \tag{464}$$

and

$$\bar{p} = (\bar{u}\bar{u}\bar{d}), \qquad \bar{n} = (\bar{u}\bar{d}\bar{d}). \tag{465}$$

Hadronization itself does not generate a net quark–antiquark asymmetry from an initially symmetric state. It reorganizes the quark and antiquark populations into hadronic degrees of freedom.

The N-conserving transition

$$\bar{n} \to p + e^- + \nu_e \tag{466}$$

has the quark-content bookkeeping

$$\bar{u} + \bar{d} + \bar{d} \to u + u + d + e^- + \nu_e. \tag{467}$$

This equation represents the quark-content change of the hadronic transition rather than a free-quark decay process.

The quantities Δ_u and Δ_d denote net flavor abundances, not the N quantum numbers of the corresponding quarks.

One $\bar{u}$ antiquark is removed and two u quarks appear in the final proton. Since

$$\Delta_u \equiv n_u - n_{\bar{u}}, \tag{468}$$

the corresponding change is

$$\delta\Delta_u = \delta n_u - \delta n_{\bar{u}} = (+2) - (-1) = +3. \tag{469}$$

Likewise, one d quark is produced while two $\bar{d}$ antiquarks are removed. Since

$$\Delta_d \equiv n_d - n_{\bar{d}}, \tag{470}$$

the corresponding change is

$$\delta\Delta_d = \delta n_d - \delta n_{\bar{d}} = (+1) - (-2) = +3. \tag{471}$$

Including the electron and electron neutrino, a single transition therefore produces

$$\left(\delta\Delta_u, \delta\Delta_d, \delta\Delta_e, \delta\Delta_{\nu_e}\right) = (+3, +3, +1, +1). \tag{472}$$

Thus, the hadron-level result

$$\left(\delta\Delta_p, \delta\Delta_n, \delta\Delta_e, \delta\Delta_\nu\right) = (+1, +1, +1, +1) \tag{473}$$

has a corresponding quark-level asymmetry structure.

Since each net proton contributes two u quarks and one d quark, while each net neutron contributes one u quark and two d quarks, the corresponding net light-quark flavor abundances satisfy

$$\Delta_u = 2\Delta_p + \Delta_n, \tag{474}$$

and

$$\Delta_d = \Delta_p + 2\Delta_n. \tag{475}$$

The inverse relations are

$$\Delta_p = \frac{2\Delta_u - \Delta_d}{3}, \qquad \Delta_n = \frac{2\Delta_d - \Delta_u}{3}. \tag{476}$$

Therefore,

$$\Delta_u + \Delta_d = 3(\Delta_p + \Delta_n), \tag{477}$$

so that the conventional net baryon number may be written as

$$B_{\text{net}} = \frac{\Delta_u + \Delta_d}{3} = \Delta_p + \Delta_n. \tag{478}$$

The difference between the two light-quark asymmetries is

$$\Delta_u - \Delta_d = \Delta_p - \Delta_n. \tag{479}$$

In the weak-isospin-based classification,

$$N(u) = +1, \qquad N(d) = -1, \tag{480}$$

with

$$N(\bar{u}) = -1, \qquad N(\bar{d}) = +1. \tag{481}$$

The net quark-sector contribution to the additive N quantum number is therefore

$$N_q = N(u)\Delta_u + N(d)\Delta_d = \Delta_u - \Delta_d. \tag{482}$$

For the representative transition considered above,

$$\delta\Delta_u = \delta\Delta_d = +3, \tag{483}$$

and hence

$$\delta N_q = N(u)\delta\Delta_u + N(d)\delta\Delta_d = (+1)(+3) + (-1)(+3) = 0. \tag{484}$$

The same result can be seen directly from the quark N assignments. The initial antineutron carries

$$N^{(q)}_{\text{initial}} = N(\bar{u}) + 2N(\bar{d}) = (-1) + (+1) + (+1) = +1, \tag{485}$$

while the final proton carries

$$N^{(q)}_{\text{final}} = 2N(u) + N(d) = 2(+1) + (-1) = +1. \tag{486}$$

Thus, the quark-sector N quantum number is conserved.

The leptonic contribution also vanishes,

$$\delta N_\ell = N(e^-)\delta\Delta_e + N(\nu_e)\delta\Delta_{\nu_e} = (-1)(+1) + (+1)(+1) = 0. \tag{487}$$

Therefore,

$$\delta N_q = 0, \qquad \delta N_\ell = 0, \qquad \delta N_{\text{tot}} = 0, \tag{488}$$

while the same process simultaneously produces

$$\delta\Delta_u > 0, \qquad \delta\Delta_d > 0. \tag{489}$$

The quark–antiquark symmetric initial state can therefore pass through hadronization without acquiring a net light-quark asymmetry from hadronization itself. For the hadronic realization considered here, subsequent CP-asymmetric N-conserving interspecies transitions can generate

$$\Delta_p > 0, \qquad \Delta_n > 0, \qquad \Delta_u > 0, \qquad \Delta_d > 0. \tag{490}$$

For the representative transition,

$$\delta\Delta_u = \delta\Delta_d = +3, \qquad \delta\Delta_p = \delta\Delta_n = +1, \tag{491}$$

so the quark- and hadron-level asymmetry orientations are generated consistently by the same microscopic process.

After confinement, Δ_u and Δ_d should be interpreted as net u- and d-flavor contents stored predominantly in baryons rather than as densities of free quarks. Antiquarks are not absent from present hadrons because QCD sea $q\bar{q}$ pairs remain present. The physically relevant quantities are the net flavor differences Δ_u and Δ_d.

Subsequent neutron–proton conversion, weak freeze-out, neutron decay, and Big Bang nucleosynthesis can modify the relative proton and neutron abundances and therefore the late-time ratio Δ_u/Δ_d.

The overall sequence may be summarized schematically as

$$\boxed{\begin{aligned} q\text{–}\bar{q}\ \text{symmetry} &\longrightarrow \text{hadronization} \\ &\longrightarrow N\text{-conserving CP-asymmetric transitions} \\ &\longrightarrow \Delta_p > 0,\ \Delta_n > 0, \quad \Delta_u > 0,\ \Delta_d > 0 \end{aligned}}\,. \tag{492}$$

This quark-level interpretation shows that the mechanism proposed in Sec. 6.3 corresponds to a genuine net quark–antiquark flavor asymmetry encoded in the hadronic abundance asymmetry. A quantitative cosmological treatment of the quark-level production rates, CP asymmetry, inverse reactions, washout, hadronization, and Boltzmann evolution is left for future work.

7 Experimental Tests and Falsifiability of the Weak-Isospin-Based N Framework

7.1 Experimental Tests of N-Conserving Four-Species Asymmetry Transitions

The N-conserving decay and scattering channels introduced in Sec. 6.3 provide direct experimental targets for the proposed species-level asymmetry mechanism. These transitions satisfy

$$\Delta N = 0, \qquad \Delta Q = 0, \qquad \Delta(B-L) = 0, \tag{493}$$

while allowing, in the conventional baryon- and lepton-number bookkeeping,

$$\Delta B = \Delta L \neq 0. \tag{494}$$

A representative $1 \to 3$ decay pair is

$$\boxed{\bar{n} \to p + e^- + \nu_e}, \qquad \boxed{n \to \bar{p} + e^+ + \bar{\nu}_e}. \tag{495}$$

The first transition produces the correlated species-level change

$$\boxed{\left(\delta\Delta_p, \delta\Delta_n, \delta\Delta_e, \delta\Delta_\nu\right) = (+1, +1, +1, +1)}. \tag{496}$$

The neutron channel has previously been studied as an exotic $|\Delta B| = 2$ decay mode within an effective-field-theory framework [21]. The corresponding antineutron decay therefore provides a direct complementary target for searches involving controlled antineutron samples.

A second experimental question is whether the CP-conjugate partial decay rates differ. Define

$$\Gamma_+ \equiv \Gamma\left(\bar{n} \to p + e^- + \nu_e\right), \qquad \Gamma_- \equiv \Gamma\left(n \to \bar{p} + e^+ + \bar{\nu}_e\right), \tag{497}$$

and

$$\epsilon_N = \frac{\Gamma_+ - \Gamma_-}{\Gamma_+ + \Gamma_-}. \tag{498}$$

For a symmetric neutron–antineutron population, a nonzero source asymmetry requires

$$\Gamma_+ \neq \Gamma_-. \tag{499}$$

The positive abundance orientation discussed in Sec. 6.3 corresponds to

$$\boxed{\Gamma_+ > \Gamma_-}, \qquad \epsilon_N > 0. \tag{500}$$

Experimental tests should also include the crossed $2 \to 2$ channels identified in Sec. 6.3. Representative examples are

$$\boxed{\bar{n} + e^+ \to p + \nu_e}, \qquad \boxed{\bar{n} + \bar{\nu}_e \to p + e^-}, \tag{501}$$

with CP-conjugate reactions

$$\boxed{n+e^- \to \bar{p}+\bar{\nu}_e}, \qquad \boxed{n+\nu_e \to \bar{p}+e^+}. \tag{502}$$

For scattering channels, the relevant CP test is a comparison of cross sections at the same center-of-mass energy and for CP-related kinematic configurations. For example,

$$\boxed{\sigma\left(\bar{n}+e^+ \to p+\nu_e\right) \neq \sigma\left(n+e^- \to \bar{p}+\bar{\nu}_e\right)}. \tag{503}$$

The broader crossed transition family, including antiproton-sector processes and their kinematic conditions, was described in Sec. 6.3. Under the high-density conditions of the early Universe, where positrons, neutrinos, and antineutrinos were abundant, kinematically allowed $2 \to 2$ collision channels may have played a more important cosmological role than the corresponding $1 \to 3$ spontaneous decays [1,17].

The central experimental questions are therefore:

Do N-conserving interspecies transitions with $\Delta B = \Delta L \neq 0$ exist, and if so, do their CP-conjugate partial decay rates or scattering cross sections exhibit a measurable asymmetry?

Observation of such a transition would establish a nonstandard interspecies conversion process capable, in principle, of changing several species-level abundance differences simultaneously. Establishing its role in the cosmological asymmetry would additionally require a measurable CP asymmetry and a quantitative kinetic analysis [2,3].

The various decay and scattering channels considered here are absent as perturbative decay or scattering processes in the renormalizable Standard Model but can arise from interactions beyond it [1,21]. In the weak-isospin-based N framework, they satisfy

$$\Delta(B-L) = 0, \qquad \Delta N = 0, \tag{504}$$

and therefore belong to the class of transitions allowed by the proposed conservation structure.

Most importantly, the representative transition

$$\bar{n} \to p+e^- +\nu_e \tag{505}$$

generates

$$\left(\delta\Delta_p, \delta\Delta_n, \delta\Delta_e, \delta\Delta_\nu\right) = (+1,+1,+1,+1), \tag{506}$$

which simultaneously points toward the observed positive proton, neutron, and electron abundance differences and the positive neutrino asymmetry derived both from the global $N_{\mathrm{tot}} = 0$ condition and from the conventional electrically neutral $B-L=0$ cosmological case.

Observation of any such process would signal physics beyond the renormalizable Standard Model and would be consistent with the additive N-conservation structure proposed here. A more discriminating test of the N framework would be a systematic pattern in which observed and excluded channels follow the corresponding N-conservation selection rule.

7.2 Basic Falsification Condition for Exact N Symmetry

The fundamental species-level particle–antiparticle classification introduced in this work is defined for fermion species by

$$\boxed{N_f = 2T_{3L}(f_L)}. \tag{507}$$

As shown in Sec. 5, for the Standard Model quark and lepton species defined by their left-handed weak-doublet orientation, the electroweak charge assignments give the derived relation

$$N_f = 2Q_f - (B_f - L_f). \tag{508}$$

The additive bosonic assignments introduced in Sec. 3 are algebraically consistent with the same relation. Since the Standard Model gauge bosons and the physical Higgs boson carry $B = L = 0$, the relation reduces in the bosonic sector to $N = 2Q$. Accordingly, for the Standard Model particle content considered in the present framework, the compact additive relation is

$$\boxed{N = 2Q - (B - L)}. \tag{509}$$

For processes involving states within this defined particle content,

$$\Delta N = 2\Delta Q - \Delta(B - L). \tag{510}$$

For an electric-charge-conserving process,

$$\boxed{\Delta N = -\Delta(B - L)}. \tag{511}$$

If N is an exact additive symmetry, then

$$\Delta N = 0. \tag{512}$$

Therefore, for a charge-conserving process involving states for which the additive N relation has been defined,

$$\Delta N = 0 \quad \Longrightarrow \quad \Delta(B - L) = 0. \tag{513}$$

This provides a direct falsification condition for the stronger exact-N hypothesis. A confirmed charge-conserving process involving such states and satisfying

$$\Delta(B - L) \neq 0 \tag{514}$$

would necessarily imply

$$\Delta N \neq 0, \tag{515}$$

and would therefore falsify exact additive N conservation in the proposed framework.

The logical direction of this test is important. The weak-isospin-based fermion classification is introduced through

$$N_f = 2T_{3L}(f_L), \tag{516}$$

independently of any assumption of exact $B - L$ conservation. The relation

$$N = 2Q - (B - L) \tag{517}$$

is derived from the fermionic electroweak charge assignments and extended consistently to the bosonic assignments used in the present framework. Consequently, under the exact-N hypothesis, $B-L$ conservation follows from electric-charge conservation for processes within the particle-content domain in which the additive N relation has been defined.

Within this domain, the two conservation conditions are algebraically equivalent for charge-conserving processes,

$$\boxed{\Delta N = 0 \iff \Delta(B-L) = 0} \qquad (\Delta Q = 0). \tag{518}$$

This algebraic equivalence does not make $B-L$ conservation the defining physical origin of the proposed N symmetry. The species-level classification and the stronger exact-N hypothesis remain conceptually distinct: the former originates from weak-isospin orientation, whereas the latter is experimentally falsifiable through a confirmed charge-conserving $B-L$-violating process within the domain of the additive relation.

The same logical direction applies to the global relation. For the Standard Model particle content with the additive N assignments defined above,

$$N_{\text{tot}} = 2Q_{\text{tot}} - (B-L)_{\text{tot}}. \tag{519}$$

Under the global electric-neutrality condition [19],

$$Q_{\text{tot}} = 0, \tag{520}$$

the proposed global symmetry condition

$$N_{\text{tot}} = 0 \tag{521}$$

therefore implies

$$\boxed{(B-L)_{\text{tot}} = 0}. \tag{522}$$

Thus, the $B-L=0$ state is not adopted as a prior condition from which $N_{\text{tot}} = 0$ is constructed. It follows from the global N-symmetry hypothesis together with electric neutrality.

The Standard Model preserves $B-L$, including under electroweak sphaleron processes, but does not require its cosmological value to vanish. Interactions beyond the renormalizable Standard Model can violate $B-L$ [2, 20]. Therefore, if global N symmetry is realized, an electrically neutral cosmological state satisfies

$$(B-L)_{\text{tot}} = 0. \tag{523}$$

In other words, $B-L=0$ is not a universal requirement of particle physics models. In the present framework, however, it is a specific consequence of global N symmetry together with electric neutrality and therefore constitutes a falsifiable condition of the framework.

7.3 Cosmic Neutrino Asymmetry and the Neutron Abundance

For the late-Universe particle inventory relevant to the present abundance relation, the macroscopic nonzero N contributions are carried by the residual proton, neutron, electron, and neutrino sectors. Global N symmetry together with global electric neutrality then gives

$$\mathcal{N}_{\nu} - \mathcal{N}_{\bar{\nu}} = \mathcal{N}_n - \mathcal{N}_{\bar{n}}. \tag{524}$$

In the present observable Universe, the antineutron abundance is negligible compared with the neutron abundance [1],

$$\mathcal{N}_{\bar{n}} \ll \mathcal{N}_n, \tag{525}$$

and therefore

$$\boxed{\mathcal{N}_\nu - \mathcal{N}_{\bar{\nu}} \simeq \mathcal{N}_n}. \tag{526}$$

In the weak-isospin-based classification, the neutron carries $N = -1$ and the neutrino carries $N = +1$. The relation above therefore provides a concrete cosmological test of the global symmetry condition

$$N_{\text{tot}} = 0. \tag{527}$$

Here, $\mathcal{N}_\nu$ and $\mathcal{N}_{\bar{\nu}}$ denote the total neutrino and antineutrino populations in the active-neutrino sector included in this bookkeeping.

The present cosmic neutrino population includes the primordial cosmic neutrino background together with neutrinos and antineutrinos produced by later astrophysical processes [1]. A present-day test of global N symmetry must therefore account for all neutrino and antineutrino populations included in the adopted active-neutrino inventory.

Likewise, $\mathcal{N}_n$ denotes the total neutron inventory entering the same cosmological bookkeeping, including neutrons bound inside nuclei and astrophysical structures.

The relevant comparison is therefore

$$\boxed{\text{total cosmic neutron inventory} \quad \longleftrightarrow \quad \text{total active-neutrino–antineutrino asymmetry}}. \tag{528}$$

Such a global measurement is extremely difficult with present experimental capabilities. Nevertheless, the relation constitutes a definite observational condition required by global N symmetry.

7.4 $B-L$ Violation and Its Distinction from Observed P and CP Violation

As established in Sec. 7.2, for states within the particle-content domain in which the additive relation

$$N = 2Q - (B - L) \tag{529}$$

has been defined, electric-charge conservation gives

$$\Delta N = -\Delta(B - L). \tag{530}$$

Therefore, a confirmed charge-conserving $B-L$-violating process within this domain would constitute a direct violation of exact N conservation,

$$\Delta(B-L) \neq 0 \quad \Longrightarrow \quad \Delta N \neq 0. \tag{531}$$

This condition is distinct from the experimentally established violations of parity and CP. Parity violation and CP violation are experimentally established in weak interactions [1], but neither phenomenon by itself implies

$$\Delta(B-L) \neq 0. \tag{532}$$

Neutron beta decay, for example,

$$n \to p + e^- + \bar{\nu}_e, \tag{533}$$

preserves both $B-L$ and the additive N balance despite being mediated by the parity-violating weak interaction.

Electroweak sphaleron processes change B and L while preserving their difference,

$$\Delta B = \Delta L, \qquad \Delta(B-L) = 0, \tag{534}$$

and are therefore compatible with exact N conservation under the additive relation defined in the present framework [2, 18].

Within conventional baryogenesis, the generation of a net baryon asymmetry requires baryon-number-changing dynamics together with the other Sakharov conditions, while lepton-number dynamics play a central role in scenarios such as leptogenesis [2, 3]. Electroweak sphaleron processes can convert part of a pre-existing $B-L$ asymmetry between the baryonic and leptonic sectors while preserving $B-L$ [2, 18].

The physical interpretation is different in the present framework. If the weak-isospin-based classification and global N symmetry correctly describe the particle–antiparticle structure of the Universe, sphaleron-mediated changes of B and L need not be invoked as a necessary origin of a fundamental global particle–antiparticle asymmetry.

Sphaleron processes themselves remain compatible with exact N conservation because they preserve $B-L$.

Neutron–antineutron oscillation corresponds at the underlying level to a direct $|\Delta B| = 2$ mixing transition,

$$n \longleftrightarrow \bar{n}, \tag{535}$$

without requiring the emission or absorption of an additional particle in the conversion itself. In intranuclear searches, the produced antineutron subsequently annihilates with a neighboring nucleon, providing the observable experimental signature [22].

For the direction

$$n \to \bar{n}, \tag{536}$$

the present classification gives

$$N: \quad -1 \to +1, \qquad \Delta N = +2, \tag{537}$$

whereas the conventional baryon number changes as

$$B: \quad +1 \to -1, \qquad \Delta B = -2, \qquad \Delta(B-L) = -2. \tag{538}$$

The reverse transition, $\bar{n} \to n$, carries $\Delta N = -2$. Therefore, neutron–antineutron oscillation as a bidirectional mixing phenomenon corresponds to

$$\boxed{|\Delta N| = 2}. \tag{539}$$

A confirmed observation of neutron–antineutron oscillation would therefore establish an $|\Delta N| = 2$ transition and directly falsify exact additive N conservation.

It would also constitute direct evidence of $|\Delta B| = 2$ baryon-number violation and $B-L$ violation in the conventional description, signaling interactions beyond the minimal renormalizable Standard Model [1, 22].

The Super-Kamiokande search found no statistically significant evidence for neutron–antineutron oscillation [22].

7.5 Dirac and Majorana Neutrinos

Whether neutrinos are Dirac or Majorana fermions has not yet been experimentally established [1]. This distinction provides a direct test of the stronger hypothesis that N is an exact unbroken additive charge.

For the chirality-independent exact additive extension considered here, the Dirac neutrino species is assigned the same N value in its left- and right-handed components,

$$N(\nu_L) = N(\nu_R) = +1. \tag{540}$$

The Dirac mass bilinear is neutral,

$$N(\bar{\nu}_L \nu_R) = -N(\nu_L) + N(\nu_R) = 0. \tag{541}$$

By contrast, after electroweak symmetry breaking, a low-energy Majorana mass term contains a same-charge bilinear of the schematic form

$$\mathcal{L}_M = -\frac{1}{2} m_M \nu_\chi^T C \nu_\chi + \text{h.c.}, \qquad \chi = L \text{ or } R, \tag{542}$$

where a left-handed Majorana mass requires an electroweak-gauge-invariant completion, such as the dimension-five Weinberg operator [1, 20].

The Majorana bilinear carries

$$N\left(\nu_\chi^T C \nu_\chi\right) = +2, \tag{543}$$

with its Hermitian-conjugate term carrying the opposite charge.

An exact unbroken additive N symmetry therefore forbids such Majorana mass terms. For a massive neutrino, it permits a Dirac mass structure while excluding a Majorana mass structure as long as N remains exact and unbroken.

Thus,

$$\begin{gathered} \text{Confirmed Majorana neutrino} \implies \text{violation of exact unbroken } N \text{ symmetry,} \\ \text{Dirac neutrino} \implies \text{consistency with exact } N \text{ symmetry, but not proof of it.} \end{gathered} \tag{544}$$

If the Majorana nature of the neutrino is experimentally confirmed, this would have two distinct implications for the present framework. First, it would violate any exact unbroken additive N symmetry, since a Majorana mass term carries nonzero N. Second, because a Majorana neutrino is self-conjugate, it would conflict with the strict interpretation of $N = +1$ and $N = -1$ as distinguishing physically distinct neutrino and antineutrino sectors.

In the conventional description, the same Majorana mass term violates additive lepton number by two units and therefore also violates $B - L$ when baryon number is unchanged.

In the present framework, the Majorana bilinear directly violates the additive N assignment by two units. Within the particle-content domain in which

$$\Delta N = -\Delta(B - L) \tag{545}$$

applies for charge-conserving processes, the corresponding $B - L$ violation is therefore mapped to the same two-unit violation of N.

Thus, a confirmed Majorana nature of the neutrino would require a departure from both exact additive lepton-number/$B - L$ conservation in the conventional description and exact unbroken additive N conservation in the present framework.

7.6 Neutrinoless Double Beta Decay

Neutrinoless double beta decay provides a direct test of exact N conservation [1, 23].

At the nucleon level within the nucleus, the relevant conversion is

$$2n \to 2p + 2e^-. \tag{546}$$

The initial and final N values are

$$N_{\text{initial}} = 2(-1) = -2, \qquad N_{\text{final}} = 2(+1) + 2(-1) = 0, \tag{547}$$

and therefore

$$\boxed{0\nu\beta\beta: \qquad \Delta N = +2}. \tag{548}$$

Equivalently,

$$\Delta(B-L) = -2, \qquad \Delta N = -\Delta(B-L) = +2. \tag{549}$$

Ordinary double beta decay,

$$2n \to 2p + 2e^- + 2\bar{\nu}_e, \tag{550}$$

instead satisfies

$$\boxed{2\nu\beta\beta: \qquad \Delta N = 0}. \tag{551}$$

Consequently,

$$\boxed{\text{exact } N \text{ conservation} \quad \Longrightarrow \quad 0\nu\beta\beta \text{ forbidden}}. \tag{552}$$

A conclusive observation of $0\nu\beta\beta$ would therefore directly falsify exact N conservation, independently of whether the dominant microscopic mechanism is light Majorana-neutrino exchange or another form of lepton-number-violating new physics.

Conversely, non-observation does not establish N symmetry because an undetectably long half-life or other suppressions may also account for the absence of a signal. No conclusive $0\nu\beta\beta$ signal has been established [1]. The first LEGEND-200 results likewise found no evidence for such a signal [23].

7.7 $SU(2)_R$ Sector and a Left–Right Symmetric Realization of N

The fundamental species-level definition remains

$$N_f = 2T_{3L}(f_L). \tag{553}$$

If one seeks a chirality-independent completion of the fermionic N assignment, a left–right symmetric gauge structure provides a natural algebraic embedding through

$$Q = T_{3L} + T_{3R} + \frac{B-L}{2}. \tag{554}$$

For the canonical left–right fermion multiplets, combining this charge relation with the derived fermionic identity

$$N = 2Q - (B-L) \tag{555}$$

gives the candidate chirality-independent extension

$$\boxed{N = 2(T_{3L} + T_{3R})}. \tag{556}$$

For canonical right-handed quark and lepton doublets, this relation gives the same N assignments to the corresponding left- and right-handed components,

$$\boxed{N(f_L) = N(f_R)}. \tag{557}$$

Canonical left–right symmetric theories provide the corresponding $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ gauge structure [12, 13]. This gauge structure provides a possible algebraic embedding of the chirality-independent fermionic N assignment.

The gauge structure alone, however, does not guarantee an exact unbroken N symmetry. A full exact-N realization additionally requires the scalar vacuum structure and the Yukawa and mass sectors to preserve N.

In particular, canonical left–right models containing Majorana mass terms for neutrinos do not realize the exact unbroken N symmetry considered in Sec. 7.5.

For the charged right-handed gauge bosons,

$$(B - L)(W_R^\pm) = 0, \qquad Q(W_R^\pm) = \pm 1, \tag{558}$$

and the additive gauge-sector extension gives

$$N(W_R^+) = +2, \qquad N(W_R^-) = -2. \tag{559}$$

The discovery of an $SU(2)_R$ gauge sector, $W_R^\pm$, or right-handed charged currents would not by itself prove the particle–antiparticle interpretation proposed here.

However, a discovered sector with matching left- and right-handed fermionic assignments consistent with

$$N = 2(T_{3L} + T_{3R}) \tag{560}$$

would provide structural support for this possible completion. Establishing an exact unbroken N symmetry would additionally require the scalar, Yukawa, and neutrino-mass sectors to preserve the same additive charge.

Conversely, non-observation of an $SU(2)_R$ sector does not falsify the fundamental species-level classification

$$N_f = 2T_{3L}(f_L); \tag{561}$$

it constrains only this possible left–right completion.

The cited ATLAS and CMS searches have placed substantial constraints on the corresponding W_R–N_R parameter space without establishing such a sector [14, 15].

7.8 Summary of Experimental Tests

The principal experimental and observational tests of the framework are summarized in Table 5.

Table 5: Principal tests of the weak-isospin-based particle–antiparticle framework.

Test	Observable condition	Interpretation
Species-level asymmetry mechanism	Searches for N-conserving $1 \to 3$ decay processes (e.g., $\bar{n} \to p + e^- + \nu_e$) and $2 \to 2$ scattering processes (e.g., $\bar{n}+e^+ \to p+\nu_e$, $\bar{n}+\bar{\nu}_e \to p+e^-$), together with CP-conjugate rate differences $\Gamma_+ \neq \Gamma_-$ or $\sigma \neq \bar{\sigma}$ [21]	Tests the proposed interspecies mechanism for generating correlated species-level asymmetries.
Global cosmology	$\mathcal{N}_\nu - \mathcal{N}_{\bar{\nu}} = \mathcal{N}_n - \mathcal{N}_{\bar{n}}$	Tests the global $N_{\rm tot} = 0$ condition together with electric neutrality in the adopted late-Universe particle inventory.
Exact conservation	Charge-conserving $\Delta(B-L) \neq 0$, including n–$\bar{n}$ oscillation or $0\nu\beta\beta$ [1, 22, 23]	Falsifies exact additive N conservation.
Neutrino nature	Dirac versus Majorana [1, 20]	Majorana nature contradicts exact unbroken additive N; Dirac nature is consistent with it but does not establish it.
Gauge structure	$SU(2)_R$, $W_R^\pm$, and $N = 2(T_{3L}+T_{3R})$ [12–15]	Tests a possible left–right completion; non-observation does not falsify the species-level classification.

8 Conclusion: Recovery of Global Particle–Antiparticle Symmetry

This study asked whether the conventional particle–antiparticle classification correctly represents the global symmetry of the Universe.

We introduced the species-level classification quantum number

$$\boxed{N_f = 2T_{3L}(f_L)} \tag{562}$$

and classified nonzero-N states according to

$$N > 0: \quad \text{particle sector}, \qquad N < 0: \quad \text{antiparticle sector}. \tag{563}$$

For the principal fermionic states considered here,

$$\boxed{N(p) = +1, \qquad N(e^-) = -1, \qquad N(n) = -1, \qquad N(\nu) = +1}. \tag{564}$$

Thus, the proton and neutrino belong to the particle sector, whereas the electron and neutron belong to the antiparticle sector. The representative weak, hadronic, stellar, and early-Universe processes examined in this work are consistent with conservation of the total additive N quantum number while redistributing N among different species.

For the Standard Model quark and lepton species defined by their left-handed weak-doublet orientation, the electroweak charge assignments imply the species-level identity [1, 7, 9]

$$N = 2Q - (B - L). \tag{565}$$

Together with the additive bosonic assignments introduced in the present framework, this relation gives, for the Standard Model particle content considered here,

$$N_{\rm tot} = 2Q_{\rm tot} - (B-L)_{\rm tot}. \tag{566}$$

Under global electric neutrality,

$$Q_{\rm tot} = 0, \tag{567}$$

consistent with stringent cosmological constraints on a possible net charge asymmetry [19], this becomes

$$N_{\rm tot} = -(B-L)_{\rm tot}. \tag{568}$$

Therefore,

$$\boxed{N_{\rm tot} = 0 \quad \Longleftrightarrow \quad (B-L)_{\rm tot} = 0 \qquad (Q_{\rm tot} = 0)}. \tag{569}$$

The logical direction is important. The condition $(B-L)_{\rm tot} = 0$ is not assumed in order to obtain $N_{\rm tot} = 0$. Rather, within the present framework, global N symmetry together with electric neutrality requires

$$(B-L)_{\rm tot} = 0. \tag{570}$$

Because this condition is not universally required by particle physics models, it constitutes a falsifiable consequence of the present framework [1,20].

The same observable fermionic content that is conventionally described as strongly matter dominated is divided, under the weak-isospin-based classification, between positive-N and negative-N sectors. Under the global condition

$$\boxed{N_{\rm tot} = 0}, \tag{571}$$

the Universe is therefore globally particle–antiparticle symmetric in the sense of the total additive N balance defined in the present framework.

The global baryon–antibaryon problem is similarly reinterpreted. During the residual nucleon weak-equilibrium epoch, for negligible lepton chemical potentials and temperatures satisfying $T \gg \Delta m_{np}$, the relation

$$n_p \simeq n_n \tag{572}$$

gives an approximately vanishing baryonic N imbalance, while the subsequent proton–neutron abundance difference follows from known weak, thermal, and nuclear evolution [1, 17].

This global result does not by itself determine the remaining species-level abundance orientation. Global N symmetry alone does not determine, for example, why protons are more abundant than antiprotons, neutrons than antineutrons, or electrons than positrons. Global symmetry and species-level abundance orientation are therefore physically distinct questions.

The present study further proposes a possible particle physics mechanism for this species-level asymmetry problem. A representative hypothetical N-conserving interspecies transition is

$$\boxed{\bar{n} \to p + e^- + \nu_e}. \tag{573}$$

The corresponding exotic neutron decay family has previously been studied within an effective-field-theory framework [21].

This transition satisfies

$$\Delta N = 0, \qquad \Delta Q = 0, \qquad \Delta(B - L) = 0, \tag{574}$$

while, in the conventional Standard Model baryon- and lepton-number bookkeeping,

$$\Delta B = \Delta L = +2. \tag{575}$$

A single occurrence produces

$$\boxed{\left(\delta\Delta_p, \delta\Delta_n, \delta\Delta_e, \delta\Delta_\nu\right) = (+1, +1, +1, +1)}, \tag{576}$$

so that the proton–antiproton, neutron–antineutron, electron–positron, and neutrino–antineutrino abundance differences can all be shifted in the same direction through a single interspecies transition.

Species-level asymmetries can therefore arise through interspecies conversion without requiring the generation of a nonzero global N asymmetry.

The stronger hypothesis of exact additive N conservation remains experimentally falsifiable. Confirmed charge-conserving $B - L$ violation, including neutron–antineutron oscillation or neutrinoless double beta decay, or confirmation of a Majorana neutrino would violate exact unbroken additive N symmetry [1, 22, 23].

Thus, the weak-isospin-based classification proposed here takes

$$\boxed{N_f = 2T_{3L}(f_L)} \tag{577}$$

as its fundamental species-level classification criterion and recovers global particle–antiparticle symmetry through

$$\boxed{N_{\text{tot}} = 0}. \tag{578}$$

At the same time, the present study does not leave the species-level abundance-orientation problem solely as an open question. It proposes N-conserving interspecies transitions, involving both decay and collision processes, as a possible particle physics source of the four correlated species-level asymmetries while preserving the global additive N balance.

A persistent cosmological asymmetry additionally requires CP-asymmetric conversion and the avoidance of complete washout by inverse processes or thermal equilibration [2, 3].

The central experimental tests of this mechanism are the existence of such transition channels and possible asymmetries between the partial decay rates or scattering cross sections of CP-conjugate channels.

The results therefore combine a reclassification that recovers global particle–antiparticle symmetry with a possible particle physics source of the species-level asymmetries and a direct experimental route for testing the proposed mechanism.

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particle physics mechanism for resolving the species-level asymmetry problem, based on N-conserving $1 \to 3$ transitions, such as $\bar{n} \to p + e^- + \nu_e$, and related $2 \to 2$ transitions, such as $\bar{n} + e^+ \to p + \nu_e$ and $\bar{n} + \bar{\nu}_e \to p + e^-$, each of which can produce the correlated asymmetry shift $(\delta\Delta_p, \delta\Delta_n, \delta\Delta_e, \delta\Delta_\nu) = (+1, +1, +1, +1)$ in a single process. Generative AI was used during the drafting and editing process to assist with exposition and language refinement. The final manuscript was independently reviewed and verified by the author, who assumes full responsibility for all scientific claims, calculations, interpretations, and conclusions.

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