Space-time curvature coupling of spinors in early universe: Neutrino asymmetry and a possible source of baryogenesis

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It is well known that when a fermion propagates in curved space-time, its spin couples to the curvature of background space-time. We propose that this interaction for neutrinos propagating in early curved universe could give rise to a new set of dispersion relations and then neutrino asymmetry at equilibrium. We demonstrate this with the Bianchi models which describe the homogeneous but anisotropic and axially symmetric universe. If the lepton number violating processes freeze out at $10^{-37}$ second when temperature $T \sim 10^{15}$GeV, neutrino asymmetry of the order of $10^{-10}$ can be generated. A net baryon asymmetry of the same magnitude can thus be generated from this lepton asymmetry either by a GUT $B - L$ symmetry or by the electro-week sphaleron processes which have $B + L$ symmetry.

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The asymmetry of neutrino in universe is a known fact. This asymmetry is thought to arise due to lepton number asymmetry, e.g., via the Affleck-Dine mechanism [1]. There are several important consequences of a large neutrino asymmetry in early universe which may have effects on production of light elements during BBN, contribution of relic neutrinos to the present energy density of universe, change of neutrino decoupling temperature, cosmic microwave background etc. [2]. Also the massive neutrinos with large asymmetry can explain the existence of cosmic radiation with energy greater than GZK cutoff [3]. Keeping all these importance in mind, our present goal is to prescribe a new mechanism which can give an insight to the origin of neutrino asymmetry fixed up in the early era.

When any fermion propagates in curved space-time its spin couples to the background curvature connection and gives rise to an interaction. The various aspects of this feature have been studied in past (e.g., [4–12]). It has also been shown that this interaction may be responsible for an additional neutrino asymmetry even in the present era of universe [13–15]. However, it is very difficult to visualize as the strength of the above mentioned interaction is negligible in our earth which is practically flat. In a similar fashion, the space-time around a black hole can generate neutrino asymmetry locally [13,15], but as we do not have overall information about number of black holes and their

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corresponding spin orientation, it is very difficult to predict whether it produces a significant asymmetry over the relic value or not. A similar mechanism to produce asymmetry was noted earlier [16]. Later, the Lorentz and the CPT violating scenarios were addressed in the context of Riemann-Cartan space-times [17] and in the neutrino sector [18], although in curved space-time a precise definition of the CPT symmetry is challenging to establish.

The important fact to note is that the interaction term, arising due to spin-curvature coupling, does not preserve CPT and is similar in its mathematical form to the effective CPT violating terms known to exist in other contexts (see, e.g., [19–21]). This interaction has opposite sign for a neutrino and an anti-neutrino, and therefore splits up their energy levels which may violate lepton symmetry in a certain situation. Therefore, if neutrinos are considered to be propagating in the non-flat early universe era, then due to presence of lepton number violating GUT processes a net asymmetry may arise between neutrinos and anti-neutrinos at the thermodynamic equilibrium. With time, as temperature goes down, this neutrino asymmetry also goes down and gets frozen-in when the lepton number violating GUT processes decouple at the era when temperature, \( T \lesssim 10^{15} \text{GeV} \). Note that according to the Linde’s chaotic inflation model [22], inflation would start at the Planck time and end at the era when temperature, \( T \sim 10^{14} - 10^{15} \text{GeV} \).

On the other hand, if inflation would start at the post Planck time [23], then again it would end at similar temperature. Therefore in either way, there is a minimum chance to wipe out this neutrino asymmetry at the end of inflation. Moreover, this neutrino asymmetry may be favored during inflation, i.e. in presence of primordial quantum fluctuations in the space-time. This is basically the tensor perturbation to early universe which also brings the off-diagonal terms in the metric responsible for the CPT violation as mentioned above. Therefore, one could argue for the gravity wave induced neutrino asymmetry in early universe.

If there is a chance to wipe out this asymmetry during inflation, the space-time curvature effect would still split up the energy of a neutrino from that of an anti-neutrino, which might give rise to an additional asymmetry solely due to the curvature effect of early universe. In presence of gravity, origin of this CPT violating interaction is an interesting result on its own right. The magnitude of neutrino asymmetry depends on the order of anisotropy as well as the time when the lepton number violating processes freeze out in the early era. Here we show that the generated neutrino asymmetry by our mechanism agrees with observation perfectly. The basic criteria to generate neutrino asymmetry in early universe through our mechanism are: (i) The space-time of early universe should have deviated from spherical symmetry. (ii) The interaction Dirac Lagrangian must be CPT violating, at least in a local frame, which may be an axial four-vector (or pseudo four-vector) multiplied by a curvature coupling four-vector potential. (iii) The temperature scale of the system should be large with respect to the energy scale of the space-time curvature.

Therefore we show that one of the possible origin of neutrino asymmetry is the anisotropic phase of early universe. As the background metric deviates from spherical symmetry, neutrino asymmetry comes out clearly. In this connection, the Dirac equation and the corresponding Lagrangian come into the picture for obvious reason. One of the key requirement to generate neutrino asymmetry by this mechanism is that the background metric should have at least one off-diagonal spatial component, if the set of coordinate variables is \( \{x, y, z, t\} \). If early universe is thought to be anisotropic, we achieve the required form of metric. On the other hand, as long as the anisotrope is low, which is good enough for the present purpose, the new cosmological data of WMAP are quite consistent with an anisotropic universe. Therefore, we consider a simplified version of Bianchi II, VIII and IX models [24]. The generalized form of
the metric is

\[ ds^2 = -dt^2 + S(t)^2 dx^2 + R(t)^2 [dy^2 + f(y)^2 dz^2] - S(t)^2 h(y) [2dx - h(y) dz] dz \]  

(1)

where for the Bianchi II, VIII and IX models, respectively \( f(y) \) and \( h(y) \) are given as

\[ f(y) = \{ y, \sinh y, \sin y \}, \quad h(y) = \{ -y^2/2, - \cosh y, \cos y \}. \]

(2)

The corresponding orthogonal set of non-vanishing components of tetrad (vierbein) can be written as

\[
\begin{align*}
e_0^1 &= 1, \quad e_1^1 = f(y) R(t) S(t) / \sqrt{f(y)^2 R(t)^2 + S(t)^2 h(y)^2}, \quad e_y^2 = R(t), \\
e_3^3 &= \sqrt{f(y)^2 R(t)^2 + S(t)^2 h(y)^2}, \quad e_x^3 = -S(t)^2 h(y) / \sqrt{f(y)^2 R(t)^2 + S(t)^2 h(y)^2}.
\end{align*}
\]

(3)

Thus the generalized Dirac Lagrangian density in absence of torsion can be given as

\[ \mathcal{L} = \sqrt{-g} \left( i \bar{\psi} \gamma^a D_a \psi - m \bar{\psi} \psi \right), \]

(4)

where the covariant derivative and spin connection are defined as

\[ D_a = \left( \partial_a - \frac{i}{4} \omega_{ba} \sigma^{bc} \right), \]

(5)

\[ \omega_{ba} = e_{b\lambda} (\partial_a e^\lambda_c + \Gamma^\lambda_{\mu\nu} e^\mu_a e^\nu_c). \]

(6)

We work in units of \( c = \hbar = k_B = 1 \). The Lagrangian is invariant under local Lorentz transformation of vierbein and spinor field as \( e^a_\mu(x) \rightarrow A^a_\mu(x) e^a_\mu(x) \) and \( \psi(x) \rightarrow \exp(i \epsilon_{ab}(x) \sigma^{ab}) \psi(x) \), where \( \sigma^{ab} = \frac{i}{2} [\gamma^a, \gamma^b] \), is the generator of tangent space Lorentz transformation. The Latin and the Greek alphabets indicate the flat and the curved space coordinates respectively. Also

\[ e^a_\mu e^\mu_a = g^{\mu\nu}, \quad e^a_\mu e^\mu_b = \eta^{ab}, \quad \{ \gamma^a, \gamma^b \} = 2 \eta^{ab}, \]

(7)

where \( \eta^{ab} \) represents the inertial frame of the Minkowski metric and \( g^{\mu\nu} \) the curved space-time metric.

If we expand eqn. (4), spin connection terms are reduced to the combination of an anti-hermitian, \( \bar{\psi} A_a \gamma^a \psi \), and a hermitian, \( \bar{\psi} B^d \gamma^5 \gamma_d \psi \), terms [25]. The anti-hermitian interaction term disappears when its conjugate part is added to the Lagrangian. The only interaction survives in \( \mathcal{L} \) is the hermitian part and then eqn. (4) reduces to

\[ \mathcal{L} = \mathcal{L}_f + \mathcal{L}_I = \sqrt{-g} \left( i \bar{\psi} \gamma^a D_a \psi - m \bar{\psi} \psi \right) \left( i \gamma^a \partial_a - m \right) + \gamma^a \gamma^5 B_a \right) \psi, \]

(8)

where

\[ B^d = e^{\alpha\beta\gamma\delta} e_{b\lambda} \left( \partial_a e^\lambda_c + \Gamma^\lambda_{\alpha\beta} e^\alpha_a e^\beta_c \right). \]

(9)

The explicit form of gravitational scalar potential, \( B_0 \) (which is the most important quantity in our formalism that we show later), can be written as

\[ B^0 = e_{1\lambda} \left( \partial_5 e^\lambda_2 - \partial_2 e^\lambda_3 \right) + e_{2\lambda} \left( \partial_1 e^\lambda_3 - \partial_3 e^\lambda_1 \right) + e_{3\lambda} \left( \partial_2 e^\lambda_1 - \partial_1 e^\lambda_2 \right). \]

(10)
Similarly, gravitational vector potentials, $B^1, B^2, B^3$, can be evaluated. From eqn. (10), it is clear that $B_0$ is zero if all the off-diagonal spatial components of the metric are zero (i.e. $g_{ij} = 0$, where, $i \neq j \rightarrow 1, 2, 3$).

In eqn. (8), the free part of the Lagrangian is same as the Dirac Lagrangian in flat space, except the multiplicative factor $\sqrt{-g}$ which is unity in flat space. The interaction part is an axial-vector multiplied by a gravitational four-vector potential. We know that the Lagrangian for any fermionic field is invariant under the local Lorentz transformation [26]. However, if the background gravitational field, $B_a$, is chosen to be constant in the local frame, then $\mathcal{L}_I$ violates CPT as well as the particle Lorentz symmetry in the local frame. For example, if $B_a$ is constant and space-like, then the corresponding fermion will have different interaction if its direction of motion or spin orientation changes, and thus results the breakdown of Lorentz symmetry in the local frame. This is the key conception of our present formalism. Similar interaction terms are considered in CPT violating theories and string theory (e.g. [19], [27]), but in the present case these originate automatically. The interaction $\mathcal{L}_I$ is observer Lorentz invariant but violates the particle Lorentz symmetry (see, e.g. [19, 26]). If $\mathcal{L}_I$ changes sign under the CPT transformation, then we understand that it does not preserve CPT. Actually, under the CPT transformation, associated axial-vector or pseudo-vector $(\bar{\psi}\gamma^a\gamma^5\psi)$ changes sign. Now, as $B_a$ is a constant coupling in the local frame, $\mathcal{L}_I$ violates CPT. If $B_a$ is treated as a background field in a local frame, then the interaction violates CPT explicitly. When there is no back-reaction of the microphysics involving the fermions on the metric and $B_a$ is considered as a fixed external field, then CPT is violated spontaneously. However, in the present case, with its functional form we can determine the explicit CPT status of $B_a$ itself along the space-time. If $B_a(x, y, z, t)$ is not an odd function under CPT $[B_a(-x, -y, -z, -t) \neq -B_a(x, y, z, t)]$, then $\mathcal{L}_I$ comes out to be a CPT violating (CPT odd) interaction along the space-time. The nature of background metric determines whether $B_a(x, y, z, t)$ is odd under CPT or not. Overall we can say, $\mathcal{L}_I$ is CPT as well as particle Lorentz violating interaction.

It can be noted in this respect that, assuming implicitly all fields are standard model fields, CPT violation necessarily implies the Lorentz violation in local field theory [28]. However, this is not valid for other Wigner classes [29] for which the Lee-Wick theorem [30] assures non-locality. Recently, a new form of CPT violation has been shown [31, 32] that arises without violating the Lorentz symmetry.

In our case, the four-vector $B_a$ is treated as a Lorentz-violating and CPT-violating spurion. However, if $B_a$ does not break the symmetry of particle Lorentz transformations in the local frame, then the CPT preserves. We plan to show that the fermion propagating in early universe governs the CPT violating interaction. It was shown in an earlier work [25] that the space-time metric could be such that the $B_a(x, y, z, t)$ is CPT odd along the space-time and therefore the overall interaction could be CPT invariant.

It is important to note that the interaction in the present formalism is different from those studied earlier which were also Lorentz violating but mainly CPT even [33]. Those studies were based on interactions in present universe which is flat one and thus excluded the interactions of fermions with background curvature. The purpose of those studies was to have high energy and high precision tests of special relativity. One could then obtain the bound on terms in the Lagrangian violating Lorentz invariance through various experiments, like cosmic ray observations, neutrino oscillations etc. We, in the present paper, concentrate on different aspects and establish that the background curvature plays an interesting role in disguise of vector $B_a$ to cause CPT violation and hence neutrino—anti-neutrino
asymmetry in presence of lepton number violating process. As applied to the phenomenology, our motivation is to seek the possible origin of neutrino–anti-neutrino asymmetry in early universe by putting bounds on parameters. It would be interesting to extend this analysis to study the phenomenological applications, e.g., neutrino oscillation as studied earlier [33].

Thus the corresponding dispersion relations for left and right chiral fields (here the neutrino and the anti-neutrino) are given by

$$\left(p_a \pm B_a\right)^2 = m^2,$$

where the upper sign corresponds to particle and the lower sign to anti-particle. Clearly the dispersion relation is modified due to presence of the CPT violating term. Now, in the case of neutrino, we can identify left handed species as particle and right handed species as corresponding anti-particle. Then, after some simple algebra, the energies for particle ($E_\nu$) and anti-particle ($E_\bar{\nu}$) are given by

$$E_\nu = \sqrt{(p - B)^2 + m^2 + B_0},$$

$$E_\bar{\nu} = \sqrt{(p + B)^2 + m^2 - B_0},$$

which indicate that neutrino and anti-neutrino propagating in presence of the space-time curvature have different energies. Thus, there is an energy gap between left handed and right handed species, which is proportional to the interaction term $B_a p^a$. When $B_a \to 0$, physically the case of Robertson-Walker universe which is spherically symmetric, this helicity energy gap disappears. Therefore, the difference of their number density in early universe, namely neutrino asymmetry, can be evaluated by the integral

$$\Delta n = \frac{g}{(2\pi)^3} \int d^3p \left[ \frac{1}{1 + \exp(E_\nu/T)} - \frac{1}{1 + \exp(E_\bar{\nu}/T)} \right].$$

If $B_0 = 0$, the integrand is an odd function of $p$ and hence $\Delta n = 0$. To have a non-zero neutrino asymmetry, $B_0$ must be non-zero whether $B_i$ ($i = 1, 2, 3$) are present or not. This is the reason that the space-time metric should have a non-zero off-diagonal spatial components for neutrino asymmetry to occur.

According to the Bianchi model (1), only $B_0$ and $B_2$ are non-zero given as

$$B^0 = \frac{S[-f^2 R^2 (h f' R + Sh') + h^2 S^2 (h f' R + Sh') + 2 f h R S (R f' - h h')]}{f^4 R^4 + f^2 h R^2 S^2},$$

$$B^2 = \frac{h[-f^2 R^2 + 2 f R S + h^2 S^2] [R S' - R' S]}{f^3 R^4 + f h R^2 S^2},$$

Now for Bianchi II:

$$B^0 = \frac{4 R^3 S + 3 y^2 R S^3 - 2 y S^4}{8 R^4 + 2 y^2 R^2 S^2},$$

$$B^2 = \frac{(4 y R^2 - 8 R S - y^3 S^2) (R S' - R' S)}{8 R^4 + 2 y^2 R^2 S^2},$$

for Bianchi VIII:
\[ B^0 = \frac{S[2 \cosh^2 y(\cosh 2y - 3)RS^2 - 4 \cosh^2 y \sinh y S^3 + 4R^3 \cosh^2 y \sinh^2 y - R^2S(5 \sinh y + \sinh 3y)]}{4(\cosh^2 y \sinh^2 y R^2S^2 + R^4 \sinh^4 y)} \]

\[ B^2 = \frac{\cosh y(S^2 \cosh^2 y + 2RS \sinh y - R^2 \sin^2 y)(RS' - R'S)}{\cos^2 y \sinh y R^2S^2 + R^4 \sin^4 y} \]

(17)

and for Bianchi IX:

\[ B^0 = \frac{S[2 \cosh^2 y(3 - \cos 2y)RS^2 - 4 \cosh^2 y \sin y S^3 - 4R^3 \cos^2 y \sin^2 y + R^2S(5 \sin y + \sin 3y)]}{4(\cosh^2 y \sin y R^2S^2 + R^4 \sin y)} \]

\[ B^2 = \frac{\cos y(S^2 \cosh^2 y + 2RS \sin y - R^2 \sin^2 y)(RS' - R'S)}{\cos^2 y \sin y R^2S^2 + R^4 \sin^2 y} \]

(18)

It is very clear from above that \( B^0 \) (and also \( B^2 \)) does not flip sign under space-inversion, i.e. for \( y \to -y \). Thus, it is not an odd function over the space-time for any of the Bianchi models and the form of \( B_0 \) is such that \( B_0(-x, -y, -z, -t) \neq \pm B_0(x, y, z, t) \). Therefore, \( B_a \) leads to CPT violation at any point \((x, y, z, t)\). As mentioned earlier, along the space-time the nature of \( B_a \) under CPT totally depends on the background metric, the space-time, where the neutrino propagates. See [25] where a space-time is chosen such that \( B_0(-x, -y, -z, -t) = -B_0(x, y, z, t) \) and hence \( \mathcal{L}_I \) is CPT invariant. However, the present case, where the space-time is chosen of early universe, brings an actual CPT violating situation into the picture.

The axial vector part of \( \mathcal{L}_I \) for particle, \( \psi \), and anti-particle, \( \psi^c \), may be expressed as

\[ \bar{\psi} \gamma^\alpha \gamma^5 \psi = \bar{\psi}_R \gamma^\alpha \psi_L - \bar{\psi}_L \gamma^\alpha \psi_R, \quad \bar{\psi}^c \gamma^\alpha \gamma^5 \psi^c = (\bar{\psi}_R \gamma^\alpha \psi^c)_R - (\bar{\psi}^c)_L \gamma^\alpha (\psi^c)_L. \]  

(19)

According to the standard model, a neutrino is left-handed and an anti-neutrino is right-handed. Therefore, in early universe, \( \mathcal{L}_I \) for a neutrino and an anti-neutrino respectively reduce as

\[ \mathcal{L}_I = -\bar{\psi}_L \gamma^\alpha \psi_B, \quad \mathcal{L}_I = (\bar{\psi}^c)_R \gamma^\alpha (\psi^c)_R B_a. \]

(20)

In addition, for the Majorana neutrinos, above \( \mathcal{L}_I \) turns out explicitly as

\[ \mathcal{L}_I = \bar{\psi}_L \gamma^\alpha \psi_B, \quad \mathcal{L}_I = -\bar{\psi}^c_L \gamma^\alpha \psi^c_B \]

(21)

for left-handed particle, \( \psi_L \), and corresponding charge conjugated particle, \( \psi^c_L \). Thus eqns. (11) and (12) are true for the Bianchi model and the neutrino asymmetry comes out off eqn. (13).

Let us now consider specifically the Bianchi II model with the choice of \( S(t) = \text{arbitrary constant} = C_1 \) [24]. Let us also consider, for simplicity, that the space-time curvature is such that \( (B_0)^2 \ll B_0 \), i.e. only the first order curvature effect is important. Thus, in the ultra-relativistic regime, we obtain from eqn. (13)

\[ \Delta n = \frac{g}{(2\pi)^2} T^3 \int_0^\infty \int_0^\pi \left[ \frac{1}{1 + e^{u - B_0/T}} - \frac{1}{1 + e^{u - B_0/T}} \right] u^2 d\theta du \]

(22)

where \( u = |\vec{p}|/T \). Therefore

\[ \Delta n \sim g T^3 \left( \frac{B_0}{T} \right). \]

(23)

As long as the lepton number violating processes are in thermodynamical equilibrium, \( \Delta n \) decreases as temperature goes down upto the decoupling limit \( (T_d) \) for the lepton number violating processes. Then the net lepton number
(here neutrino asymmetry) to entropy density (which is given as \( s \sim T^3 \)) remains constant after decoupling and is given as

\[
\Delta L(T < T_d) = \frac{\Delta n}{s} \sim \frac{B_0}{T_d}. \tag{24}
\]

If the lepton number violating GUT processes decouple at \( T_d \sim 10^{28} \text{K} \sim 10^{15} \text{ GeV} \), when the age of universe, \( t \sim 10^{-37} \text{ second} \), then the scale factor at that time could be given by \( R(t) \propto 10^{-19} (R(t) = (C_2 t - C_3)^{1/2}, \) when \( C_2, C_3 \) are arbitrary constants). Thus, we can obtain \( B_0 \sim 10^5 \text{ GeV} \). Therefore, from eqn. (24), neutrino as well as lepton asymmetry comes out to be \( 10^{-10} \), which matches perfectly with observation. In general, a formula for lepton asymmetry in early universe can be given by

\[
\Delta L(T < T_d) \sim 10^{-10} \left( \frac{B_0}{10^5 \text{GeV}} \right) \left( \frac{10^{15} \text{GeV}}{T_d} \right). \tag{25}
\]

Therefore, we propose a new mechanism to generate neutrino as well as lepton asymmetry in early universe. We have explicitly demonstrated this when neutrinos are considered to be propagating in a space-time of early universe. The only requirement to generate neutrino asymmetry in this mechanism is that the early universe metric should have at least a non-zero space-space cross term (i.e. the off-diagonal spatial component; \( g_{ij}, i \neq j \rightarrow 1, 2, 3 \) ) when the set of space-time coordinate is \( \{x, y, z, t\} \). It is seen that, in presence of any \( g_{ij} \), the scalar potential part (\( B_0 \)) of space-time coupling is non-zero which is actually responsible for neutrino asymmetry in universe. If all \( g_{ij} \)s are zero, \( B_0 \) and hence \( \Delta n \) vanish.

An important point to note is that after a long time, the homogeneous and anisotropic Bianchi model reduces to the space-time of present universe which is isotropic. This is easily understood from the corresponding form of shear scalar. For the Bianchi II model (which is mainly used for the calculations of various parameters in this problem), the shear scalar is obtained as \( \sigma^2 \sim 1/t^2 \), which reduces to zero as \( t \rightarrow \infty \). Therefore, although universe starts with an anisotropic phase, with the choice of anisotrope consistent with WMAP, it restores the complete isotropy at later period and reduces to that of present universe.

Our mechanism essentially works in presence of a pseudo-vector term \( \bar{\psi} \gamma^a \gamma^5 \psi \) multiplied by a background curvature coupling \( B_a \). This is the CPT and the particle Lorentz violating term, which picks up an opposite sign in between neutrino and anti-neutrino. Thus we propose, to generate neutrino asymmetry in early universe, all the following criteria have to be satisfied simultaneously: (i) The space-time must not be spherically symmetric. (ii) The interaction Dirac Lagrangian must have a CPT violating term, at least locally, which may be an axial-vector (or pseudo-vector) multiplied by a curvature coupling four-vector potential. (iii) The temperature scale of the system should be large with respect to the energy scale of the space-time curvature.

The early universe is a favorable era when all the above conditions would satisfy. It would be interesting to explore further theoretical and phenomenological consequences of the role of background gravitational curvature for neutrinos, which might offer new insights in the interplay of gravity and standard model interactions and specially of neutrino physics.

An interesting consequence of this fact may be the following. As GUT has \( B - L \) symmetry, due to asymmetry of \( L \), a baryon (\( B \)) asymmetry may be generated of the same magnitude and sign as of lepton (neutrino) asymmetry.
On the other hand, $B + L$ conservation of the sphaleron may give rise to a baryon asymmetry of same magnitude and sign as of lepton asymmetry generated in the GUT. Thus we may pinpoint about the baryogenesis in universe. A class of explicit CPT violating terms in the Lagrangian, which can generate baryon asymmetry, have been studied in [34]. However, in our case, the basic origin of this CPT violating interaction and its connection to baryon asymmetry are different and inherent. It can be noted that the inclusion of torsion does not alter our basic result. The presence of torsion only modifies the form of $B^d$ in eqn. (9) without affecting the underlying physics.

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