Baryon number violation in particle decays

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(Received 19 November 2001; published 25 March 2002)

It has been argued in the past that in baryogenesis via out-of-equilibrium decays one must consider loop diagrams that contain more than one baryon number violating coupling. In this paper we argue that the requirement with regard to baryon number violating couplings in loop diagrams is that the interaction between the intermediate on-shell particles and the final particles should correspond to a net change in baryon number and that this can be satisfied even if the loop diagram contains only one baryon number violating coupling. Put simply, we show that to create a baryon asymmetry there should be net \( B \) violation to the right of the “cut” in the loop diagram. This is of relevance to some works involving the out-of-equilibrium decay scenario.

DOI: 10.1103/PhysRevD.65.083504 PACS number(s): 98.80.Cq

It is well known that to obtain a baryon asymmetry in the out-of-equilibrium baryon number violating decays of heavy particles one must consider the interference between tree level diagrams and higher order loop diagrams. Furthermore, some particles in the loop must be able to go on shell for the net asymmetry to be nonzero. This is typically illustrated by drawing a “cut” through the lines representing particles that have gone on shell. In the Appendix of Ref. [1], the authors had argued that a further requirement is that one must consider loop diagrams that contain more than one \( B \) violating coupling. In this brief note we argue that the requirement with regards to \( B \) violating couplings is that the interactions on the right of the “cut” should correspond to a nonzero change in the baryon number. Furthermore, this can be satisfied even if the loop diagram contains only one \( B \) violating coupling and we refer the reader to such an example.

Consider a particle \( X \) and its antiparticle \( X^\prime \) each of which can decay to final states with different baryon number. Let \( f \) be a specific final state with baryon number \( B_F \) that \( X \) decays to. Assuming \( CP \) violation, the partial decay rates for \( X \) going to specific final states and for \( X^\prime \) going to the corresponding final states can be different. Therefore we now consider the amplitude \( A(\bar{X}\to\bar{f}) \) for the decay of \( \bar{X} \) to \( \bar{f} \). By the \( CPT \) theorem,

\[
A(\bar{X}\to\bar{f})=A(f\to\bar{X}).
\]

Therefore

\[
\langle f|\bar{X}\rangle_{in}=\langle f|X\rangle_{out}. \tag{2}
\]

Inserting a complete set of in states

\[
\langle X|f\rangle_{in}\sum_{\hat{g}}\langle \hat{g}|f\rangle_{in}=\langle X|f\rangle_{in}\sum_{\hat{g}}\langle \hat{g}|f\rangle_{in}. \tag{3}
\]

The sum over states above includes integration over momenta. Then

\[
\sum_{\hat{f}_{B_F}}|\langle \hat{f}_{B_F}|X\rangle|^2=\sum_{\hat{f}_{B_F}}\sum_{\hat{g}}\langle X|\hat{g}\rangle_{out}\langle \hat{g}|f\rangle_{in}\langle f|X\rangle_{in} \tag{4}
\]

\[
=\sum_{\hat{f}_{B_F}}\sum_{\hat{g}}\langle X|\hat{g}\rangle_{out}\langle \hat{g}|f\rangle_{in}\langle f|X\rangle_{in}
\]

\[
=\sum_{\hat{f}}\sum_{\hat{g}}\langle X|\hat{g}\rangle_{out}\langle \hat{g}|f\rangle_{in}\langle f|X\rangle_{in}\sum_{\hat{f}_{B_F}}\sum_{\hat{g}}\langle X|\hat{g}\rangle_{out}\langle \hat{g}|f\rangle_{in}\langle f|X\rangle_{in}
\]

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‡ The issue of whether it is possible to have unstable particles in asymptotic states [2] is ignored in Ref. [1] and by us.
§As in Ref. [1], we shall henceforth drop the subscript for the \( |X\rangle \) states as \( |X\rangle_{\text{in}}=|X\rangle_{\text{out}} \) for one particle states.