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Electroweak sphaleron under multiple-step EWPT with the general high dimensional SU(2) multiplet extension to the Standard model

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In this study, we present a comprehensive analysis of the electroweak sphaleron formalism and its application to the electroweak phase transition (EWPT). We offer an equivalence proof for various sphaleron configurations and construct the previously unestablished high-dimensional $SU(2)$ sphaleron transformation matrix. Furthermore, we provide an in-depth examination of non-contractible loops and sphaleron boundary conditions. Besides the sphaleron formalism, we investigate the intricacies of the multi-step EWPT. We showcase two distinct analytical approaches for extending the $SU(2)$ scalar multiplet to the standard model (SM) under differing EWPT scenarios, and perform an explicit calculation of the sphaleron energy using a septuplet example. In the context of a single-step EWPT leading to a mixed phase, we find that the additional multiplet's contribution to the sphaleron energy is negligible, primarily due to the prevailing constraint imposed by the ρ parameter. Conversely, in a two-step EWPT scenario, the sphaleron energy can achieve significantly high values during the initial phase, thereby markedly preserving baryon asymmetry if the universe undergoes a first-order EWPT.

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