

# The Adiabaticity Condition Revisited: Necessary but not Sufficient

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We present a simple counterexample that illustrates the fact that a standard expression of the adiabaticity condition –

$$abs\dot{\omega}/\omega^2$$

$abs \ll 1$ , where  $\omega$  corresponds to the characteristic frequency of any given field mode – is a necessary but not sufficient condition for particle production. We further illustrate this via the example of a Mukhanov-Sasaki-like variable corresponding to a massless test scalar field on time dependent backgrounds where in and out states can be defined, and show that the trace log for the latter has no imaginary contributions, even as the adiabaticity condition is nominally violated for certain field modes at some time. To understand these examples, we first re-examine the equivalence of physical observables derived from in-out amplitudes under field redefinitions (otherwise known as the equivalence theorem) under general spacetime dependent field redefinitions, clarifying the conditions under which it fails to apply via functional methods and LSZ reduction. We then identify the insufficiency of the adiabaticity condition as a failure of the former to be an unconditional proxy for adiabatic evolution, and restate the general conditions for the latter. We conclude by discussing the ramifications and cautions that follow from this result to familiar applications in cosmology as well as regularization schemes that rely upon an adiabatic expansion.

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