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Majoron Potential by Majorana fermion Loops

We present a diagrammatic framework for radiative Majoron potentials induced by an explicit Majorana mass M. Classifying one-loop diagrams by the number of fermion-number-violating ($N_{\rm FNV}$) and fermion-number-preserving ($N_{\rm FNP}$) propagators yields a heavy-mass scaling rule: pure FNV amplitudes behave as M^{4-n}, while mixed diagrams receive additional suppression from momentum numerators. After removing the dominant tadpole by a matching condition, the bubble diagram provides the leading Majoron mass $\propto y^2 M^2$. The mixed FNV/FNP triangle supplies the complete next-to-leading $\mathcal{O}(yv/M)$ correction through a $\cos\theta$ harmonic after vacuum alignment. We analyze the one-loop Coleman-Weinberg potential for the full two-field space $V_{\rm eff}(r,\theta)$, derive the quantum-shifted vacuum and scalar Hessian, and identify the parameter conditions required for local stability. The heavy Majorana fermion decouples from irrelevant operators but leaves non-decoupling threshold corrections to relevant symmetry-breaking operators. At finite temperature, the explicit breaking spurion M induces a thermal tadpole $\propto MT^2 r\cos\theta$. This term prevents the origin from ever being a stationary point, ensuring that the radial vacuum expectation value remains non-zero at all temperatures. Consequently, the system undergoes a smooth crossover rather than a true symmetry-restoring phase transition, and the pseudo-Goldstone description remains rigorously valid across all temperature regimes. The resulting effective potential is a periodic non-linear sigma model whose Wilson coefficients follow a two-parameter lattice classification.

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