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Complex Langevin simulation of the Lorentzian type IIB matrix model

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The type IIB matrix model has been studied as a candidate of non-perturbative formulation of superstring theory. In particular, by Monte Carlo simulation of the Lorentzian type IIB matrix model, (3+1)-dimensional expanding space-time was shown to emerge dynamically. With its detailed analysis, we found that the emergent 3-dimensional space is essentially described by the Pauli matrices, we call this structure as the Pauli-matrix structure. In fact, the Monte Carlo simulation of the Lorentzian type IIB matrix model has the sign problem. Therefore, we had used an approximation to avoid the sign problem in the previous works. However, there is a subtlety in the approximation, and it might cause the Pauli-matrix structure. In this work, we generalize the model by introducing two parameters which are related to the Wick rotation on the world sheet and in the target space. We perform the complex Langevin simulation of the generalized model to overcome the sign problem. As a result, we can see a deviation from the Pauli-matrix structure as we approach to the original model without losing the expanding behavior.

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