氏　　　名	青木　俊紘
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（様式３）

博士論文の要旨

氏　　名 青木 俊紘

論文題目
Numerical simulations of the space-time structure in the Lorentzian type IIB matrix model

The type IIB matrix model was proposed as a non-perturbative formulation of superstring theory in 1997. Monte Carlo simulation of its Lorentzian version is arduous hard due to the phase factor in the partition function. The importance sampling is not applicable as it is, and one has to face the sign problem if one uses reweighting for this factor. In our work, as well as in the previous Monte Carlo studies, the sign problem had been avoided by integrating out the scale factor of the bosonic matrices first and using a certain approximation. In this way, the simulations of its Lorentzian version showed that not only space but also time dynamically emerge.

Furthermore, it suggested that (3+1)D expanding space-time start to expand at some critical time. This numerical result implies that the expanding (3+1)D space-time naturally appears from (9+1)D space-time, where superstring theory is defined. The expanding behavior was scrutinized by simulating simplified versions of the model, which showed that the expansion is exponential at the beginning, and it turns into a power law at later times. This intriguing property is reminiscent of the inflation and the FRW universe, respectively.

In our work, we investigated the space-time structure of the matrix configurations generated by Monte Carlo simulation of the Lorentzian type IIB matrix model and its simplified models. In particular, we calculated the eigenvalues of the submatrices of the spatial matrices corresponding to each time slice and found that only two eigenvalues grow in magnitude after the critical time. A more detailed analysis showed that the expanding 3D space is described substantially by the Pauli matrices. We observed that the situation remains unaltered even at late times or in the continuum limit for the simplified models, and it is shared by the original model with maximal supersymmetry as well. This research raises the critical question of whether this model can generate a 3D space with continuum geometry.

Here we have attributed the problem to the approximation used to avoid the sign problem in this simulation since the function obtained after integrating out the scale factor is complex-valued, and the effect of the phase is not taken into account. We have argued that a "regular" space-time may be obtained if the phase factor is used correctly.

To overcome the sign problem instead of using the approximation as mentioned above, we have been exploiting the complex Langevin simulation, which was invented to make simulations of models with complex action feasible. In this simulation, we introduce two deformation parameters corresponding to the Wick rotations on the worldsheet and in the target space, respectively. These parameters enable us to interpolate between the Lorentzian version and the Euclidean version. This deformation parameter space includes the approximate model investigated in Monte Carlo studies, where we do not have the sign problem. Therefore, to stabilize the complex Langevin simulation, we start the simulation with the parameters and progress to the original model, while we tune the worldsheet and the target space deformation parameter.

Note that the Lorentzian type IIB matrix model needs to be regularized in some way or another because the phase factor in the partition function cannot suppress the contribution from the bosonic matrices with arbitrary large elements. Here we use the infrared cutoffs on both the spatial and temporal matrices analogous to the ones used in the previous work. In our algorithm, we improve the treatment of these infrared cutoffs. The basic idea is to treat the constraints by rescaling spatial and temporal matrices instead of constraining them by some strong potential, which mimics the delta function. This improvement enables us to investigate a much broader range of deformation parameters, and then approach our target, namely the original model.

In this thesis, we mainly investigate a more uncomplicated (5+1)D bosonic model in its Lorentzian version to avoid time-consuming. Our results show a transition from the Pauli-matrix structure to a smooth space-time structure, when we approach the Lorentzian model. We expect that the parameter region closer to the original model becomes accessible at larger-N. Whether a classical smooth classical space-time picture appears in that limit at a sufficiently late time is an important open question, which can be answered in accordance with the method proposed by this work. We also hope that this simulation method, as well as the obtained results discussed in this thesis, is useful in investigating the dynamics of the Lorentzian type IIB matrix model further.

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Results of the doctoral thesis screening

博士論文審査結果

Name in Full
氏　名　青木　俊紘

Title
論文題目　Numerical simulations of the space-time structure in the Lorentzian type IIB matrix model

青木俊紘君の学位論文は、超弦理論の非摂動的定式化に基づく時空構造の数値的研究に関するものである。この定式化は1997年に提唱されたtype IIB matrix modelと呼ばれるものであり、これまで20年以上にわたり、様々な角度から研究されてきた。特に、(9+1)次元の時空上で定義される超弦理論から、如何にして我々の住む(3+1)次元の時空が現れるかは、最も基本的かつ重要な問題であり、多くの研究がなされてきた。特にローレンツ型の模型に関しては、2011年にKim・西村・土屋が行った数値計算により、(9+1)次元の微視的宇宙から(3+1)次元の膨張宇宙が現れる振る舞いが確認された。青木君はこの結果をふまえ、時空の詳細な構造を数値的に調べた。その結果、膨張は３方向に起こるものの、その膨張を担っているのは２つの固有値だけであることを見いだした。この問題は、ローレンツ型の模型に現れる符号問題を避けるために用いられた近似に原因があると考えられ、こうした近似を用いない方法として、複素ランジュバン法を用いた計算が行われた。この計算では、ローレンツ型の模型に現れる作用に新たに２つのパラメータを導入し、そのパラメータを変えながら時空の構造を調べられた。その結果、もともとの模型に近いパラメータ領域で、上記の特異な時空構造が解消し、多くの固有値が空間の膨張に関与する振る舞いが確認された。これは、超弦理論の非摂動的定式化であるtype IIB matrix modelから、(3+1)次元の連続的な時空が現れることを示唆する重要な結果である。

これらの結果は学術的に十分な価値が認められるものであり，博士論文の内容として必要な水準を満たしていると判断し，本論文が学位の授与に値すると判断した。