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科学研究費助成事業　　研究成果報告書

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研究課題名（和文）Connecting the QCD vacuum with experimental observables through realistic proton-nucleus reaction simulations

研究課題名（英文）Connecting the QCD vacuum with experimental observables through realistic proton-nucleus reaction simulations

研究代表者

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研究者番号：００６３２３９０

交付決定額（研究期間全体）：（直接経費）　　2,100,000円

研究成果の概要（和文）：この研究の目的は、ベクトル・メソンのオフシェルのダイナミックスも取り扱える最先端のトランスポート・フレームワークを駆使し、陽子・原子核(pA)反応の数値シミュレーションを実施することで、核物質中のphi中間子の質量変化を解析することにあった。その結果、有限密度における強い相互作用のカイラル対称性のオーダーパラメーターに制限を与えることができる。
結果として、KEK及びJ-PARCにて研究されるpA反応の現実的なシミュレーションには成功したが、phi中間子の質量変化を確実に同定するためにはより精度の良い実験データの観測及びpA反応コードの開発を含むさらなる研究が必要だということが分かった。

研究成果の学術的意義や社会的意義
The research of this project will help to clarify the the origin of the visible (hadronic) mass in our universe. This mass is thought to be generated by the spontaneous breaking of the chiral symmetry of the strong interaction, but this assumption has so far never been experimentally confirmed.

研究成果の概要（英文）：The purpose of this project was to perform numerical simulations of proton-nucleus (pA) reactions, making use of a state-of-the-art transport framework, that can particularly treat the off-shell dynamics of vector mesons, with the goal of studying the mass modification of the phi meson in nuclear matter. The result of this analysis can be used to constrain the order parameter of chiral symmetry of the strong interaction at finite density.
During the research period, we succeeded in conducting realistic transport simulations of the pA reactions probed at KEK and J-PARC, but found that for clearly determining the mass shift of the phi meson in nuclear matter, more work will be needed in the future, including the measurement of more precise dilepton data from pA reactions and the further development of pA reaction simulations.

研究分野：ハドロン物理学

キーワード：強い相互作用　ベクトル・メソン　phi中間子　核物質　カイラル対称性

１．研究開始当初の背景

The background of this research project is related to the problem of understanding the origin of the visible (hadronic) mass in our universe. While the Higgs field generates bare masses for the quarks, it does not explain the heaviness of hadronic masses, which is theoretically expected to be caused by the breaking of chiral symmetry of the strong interaction (Quantum ChromoDynamics, QCD) and the ensuing formation of the so-called chiral condensate. While this mechanism is relatively well understood from a theoretical point of view, it has so far never been directly confirmed in an experimental measurement.
In this situation, it has been proposed to probe the chiral condensate and especially its reduction at finite density by measuring the masses of light vector mesons in nuclear matter [1,2]. This is so because QCD sum rules calculations have shown such vector mesons to be sensitive to the magnitude of the chiral condensates of u, d and s quarks. In the past two decades, many efforts were dedicated to the study the ρ meson at finite density, which is a vector meson mostly sensitive to the chiral condensate of u and d quarks. Because the ρ meson undergoes strong broadening in nuclear matter, it has however turned out to be difficult to measure its mass change at finite density. Therefore, the focus has in recent years been laid on the φ meson, which is another vector meson mainly sensitive to the chiral condensate of the s quark, is expected to be less broadened in nuclear matter and hence an easier target for an experimental measurement.
To study the mass of the φ meson at finite density in actual experiments, pA (proton-nucleus) reactions are most commonly used. In such reactions, the φ meson is produced at both the surface and center of the target nucleus and subsequently moves around in the nucleus before leaving the dense target region. At some time during this process, it can decay into a dilepton pair (electron and positron), which are then measured in the experiment. It hence, experiences many different densities during the whole reaction, which should therefore be well understood to be able to accurately interpret the resultant dilepton spectrum. For this purpose, realistic numerical simulations of the corresponding reactions are indispensable.

２．研究の目的

The purpose of this project was to perform numerical simulations of pA reactions making use of a state-of-the-art transport framework, that can particularly treat the off-shell dynamics of vector mesons, which is important in view of the broadening phenomenon that (besides the more interesting and relevant mass shift) can happen to vector mesons at finite density. The specific goals of the project were the following:
(1) Performing realistic numerical simulations of pA reactions probed at KEK and J-PARC
(2) Determine the mass shift of the φ meson in nuclear matter by combining experimental data with the numerical simulations
(3) Determine the change of the strange quark chiral condensate in nuclear matter

Fitting the dilepton spectra obtained from the transport simulations of goal nr. 1, in which multiple scenarios with different φ meson mass shifts were assumed, to the available experimental data, one can determine which mass shift scenario best fits the data and thus goal nr. 2 can be achieved. Using the theoretical results of QCD sum rules, the mass shift can then further be related to the chiral condensate of the s quark, which leads to goal nr. 3.

３．研究の方法

For the purpose of this project, we made use of the PHSD transport code that was developed by Cassing and Bratkovskaya and is equipped to treat both mass shift and broadening scenarios (or combinations of them) of vector mesons at finite density [3,4]. Using this code, we first simulated 12 GeV pA reactions (e.g. the kinetic energy of the incoming proton in the lab frame equals 12 GeV) with Carbon and Copper nuclear targets. These correspond to the reactions probed at the KEK E325 experiment [5]. In these simulations, once φ mesons (as well as other vector mesons) are generated, the shining method is employed to compute the respective dilepton contribution. This method assumes that the vector mesons and constantly

emitting dilepton pairs at each time step of the simulation, which helps to gain enough statistics for these in reality rather rare electromagnetic decays. Once the total dilepton spectrum for the whole reaction is obtained, further experimental effects such as the limited experimental resolution for the energy and momenta of the dileptons are incorporated into the dilepton spectrum, which is finally fitted to the available experimental data of the KEK E325 experiment.
We have also simulated similar 30 GeV pA reactions with the same Carbon and Copper nuclear targets, which will be measured at the future J-PARC E16 and E88 experiments. We have in these simulations especially studied the K^+K^- decays of the φ mesons and the final state interactions of the outgoing kaons with the surrounding nuclear matter, as these will be the main target of the E88 experiment.

４．研究成果

Using the method described in the previous two sections, we have computed the dilepton spectra of 12 GeV pC and pCu reactions. As an example, the spectrum obtained from the pCu reaction in the region of the φ meson mass is shown in Fig. 1 for several scenarios with

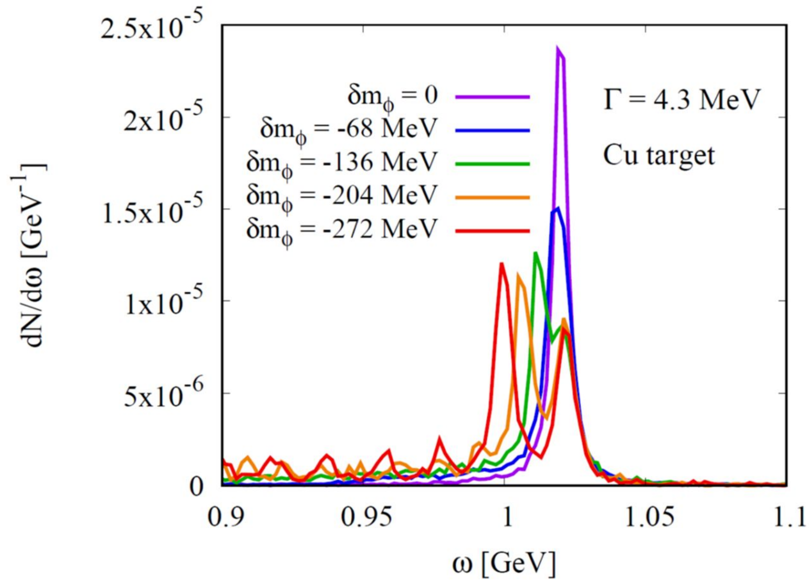

Fig. 1: Dilepton spectrum in the φ meson mass region for several in-medium mass shift scenarios without broadening effects.

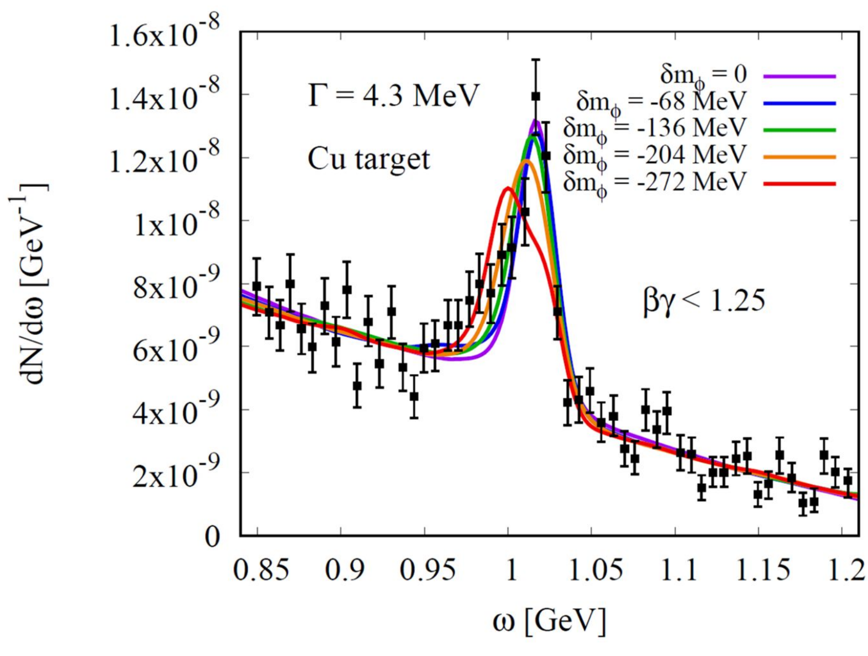

Fig. 2: Fit of the dilepton spectrum in the φ meson mass region for several in-medium mass shift scenarios without broadening effects to the experimental data of the KEK E325 experiment.

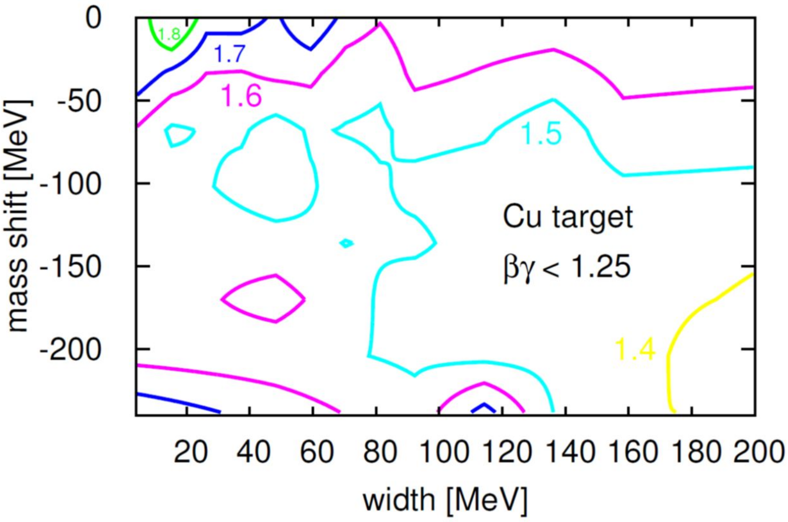

Fig. 3: χ^2/d.o.f values of fits of the dilepton spectrum in the φ meson mass region for several mass modification and broadening scenarios.

different mass shifts, but no broadening effects. After applying experimental effects such as limited resolution, this spectrum can be fitted to the experimental data of the KEK E325 experiment, where we assume a third order polynomial for the background. The result is shown in Fig. 2, for the same scenarios that were already shown in Fig. 1. As can be seen in Fig. 2, the quality of the fit differs considerably depending on which mass shift scenario is taken. Next, the quality of all simulated modification scenarios are compared in Fig. 3 in terms of χ^2/d.o.f values for φ mesons with small momenta in the lab frame ($\beta\gamma < 1.25$). As can be observed in this plot, the best fits are realized for simulations with both mass shift and broadening. The best fit is specifically obtained for a mass shift of -204 MeV and a decay width of 202 MeV at normal nuclear matter density (in the simulation, we assume a linear dependence of both mass shift and width increase on the density).
As discussed in the previous paragraph, we found from our transport simulation that the mass shift of -204 MeV can best reproduce the experimental data of the KEK E325 experiment. As can however be seen in Fig. 3, other scenarios give very similar χ^2/d.o.f values, suggesting the need of more precise experimental data for reaching a more definite conclusion. Generally, the negative mass shift values that give a reasonably good fit to the experimental data are much larger than those reported in the original experimental paper of Ref.[??], which further hints at the existence of large systematic uncertainties is the analysis of the experimental data, which have to be investigated further in the near future, especially in light of the future J-PARC E16 and E88, which will start measuring physics data in the next few years. The results of the transport simulations discussed here have so far been published in several conference proceedings [6,7], while a full paper describing the obtained results in detail, is in preparation [8]. In addition, two papers in close relation with this project were published: 1) A paper improving the previous QCD sum rule calculation on the behavior of the φ meson in nuclear matter [9], 2) A paper as a result of a collaboration between theoretical and experimental researchers, discussing the angular distributions of the dilepton and K^+K^- decays of the φ meson [10].
As mentioned in the previous section, we have during the course of this project also simulated 30 GeV pC and pCu reactions, which will be measured at the J-PARC E16 and E88. As these experiments have currently not started yet, we could not compare our results to any available experimental data. However, we could provide the results of our simulation especially to the members of the E88 collaboration, which used them to compose their experimental proposal to the J-PARC Program Advisory Committee, which approved it as a Stage-1 status experiment as a result of the submitted proposal [11].

Overall, the first and most important goal of this project, which was to conduct realistic transport simulations of the pA reactions probed at KEK and J-PARC was achieved successfully. For completing the second and third goal, that is, determining the mass shift of the φ meson in nuclear matter and using it to constrain the s quark chiral condensate at finite density, more work will be needed in the future. This includes the measurement of more precise dilepton data from pA reactions and the further development of pA reaction simulations to be able to interpret the measured dilepton spectra with less ambiguity.

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５．主な発表論文等

〔雑誌論文〕　計13件（うち査読付論文　13件／うち国際共著　8件／うちオープンアクセス　8件）

１．著者名 Pavao Rafael、Gubler Philipp、Fernandez-Soler Pedro、Nieves Juan、Oka Makoto、Takahashi Toru T.	４．巻 820
２．論文標題 The negative-parity spin-1/2 \Lambda baryon spectrum from lattice QCD and effective theory	５．発行年 2021年
３．雑誌名 Physics Letters B	６．最初と最後の頁 136473～136473
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.physletb.2021.136473	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名 Gubler Philipp	４．巻 62
２．論文標題 Studying the Phi Meson in Nuclear Matter by Simulating pA Reactions in a Transport Approach	５．発行年 2021年
３．雑誌名 Few-Body Systems	６．最初と最後の頁 1～5
掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/s00601-021-01634-z	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

１．著者名 Meng Qi、Hiyama Emiko、Hosaka Atsushi、Oka Makoto、Gubler Philipp、Can Kadir Utku、Takahashi Toru T.、Zong Hongshi	４．巻 62
２．論文標題 Prediction of Double-heavy Tetraquarks Bound States in Quark Model	５．発行年 2021年
３．雑誌名 Few-Body Systems	６．最初と最後の頁 1～5
掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/s00601-021-01665-6	査読の有無 有
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１．著者名 Gubler Philipp	４．巻 380
２．論文標題 The phi meson in nuclear matter in a transport approach	５．発行年 2022年
３．雑誌名 Proceedings of Science	６．最初と最後の頁 1～5
掲載論文のDOI（デジタルオブジェクト識別子） 10.22323/1.380.0215	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 －

１．著者名 Gubler Philipp	４．巻 -
２．論文標題 Studying the phi meson in nuclear matter from simulated pA reactions	５．発行年 2020年
３．雑誌名 Hadron Spectroscopy and Structure	６．最初と最後の頁 694-698
掲載論文のDOI（デジタルオブジェクト識別子） 10.1142/9789811219313_0119	査読の有無 有
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１．著者名 Taya Hidetoshi, Park Aaron, Cho Sungtae, Gubler Philipp, Hattori Koichi, Hong Juhee, Huang Xu-Guang, Lee Su Houng, Monnai Akihiko, Ohnishi Akira, Oka Makoto, Yang Di-Lun	４．巻 102
２．論文標題 Signatures of the vortical quark-gluon plasma in hadron yields	５．発行年 2020年
３．雑誌名 Physical Review C	６．最初と最後の頁 021901, 1-6
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevC.102.021901	査読の有無 有
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１．著者名 Gubler Philipp	４．巻 2249
２．論文標題 Simulating pA reactions to study the phi meson in nuclear matter at J-PARC	５．発行年 2020年
３．雑誌名 AIP Conference Proceedings	６．最初と最後の頁 030002, 1-7
掲載論文のDOI（デジタルオブジェクト識別子） 10.1063/5.0008659	査読の有無 有
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１．著者名 Kim Jisu、Gubler Philipp、Lee Su Houng	４．巻 105
２．論文標題 Phi meson properties in nuclear matter from QCD sum rules with chirally separated four-quark condensates	５．発行年 2022年
３．雑誌名 Physical Review D	６．最初と最後の頁 114053-(1～9)
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevD.105.114053	査読の有無 有
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1．著者名 Park In Woo、Sako Hiroyuki、Aoki Kazuya、Gubler Philipp、Lee Su Houng	4．巻 107
2．論文標題 Disentangling longitudinal and transverse modes of the phi meson through dilepton and kaon decays	5．発行年 2023年
3．雑誌名 Physical Review D	6．最初と最後の頁 074033-(1～9)
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevD.107.074033	査読の有無 有
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1．著者名 Gubler Philipp、Yamamoto Naoki、Yang Di-Lun	4．巻 2022
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3．雑誌名 Journal of Cosmology and Astroparticle Physics	6．最初と最後の頁 025-(1～37)
掲載論文のDOI（デジタルオブジェクト識別子） 10.1088/1475-7516/2022/09/025	査読の有無 有
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2．論文標題 Contribution of the Weinberg-type operator to atomic and nuclear electric dipole moments	5．発行年 2022年
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掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/JHEP06(2022)072	査読の有無 有
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1．著者名 Gubler Philipp、Bratkovskaya Elena	4．巻 271
2．論文標題 Studying phi meson properties in nuclear matter from dilepton and K^+K^- decays	5．発行年 2022年
3．雑誌名 EPJ Web of Conferences	6．最初と最後の頁 09004-(1～4)
掲載論文のDOI（デジタルオブジェクト識別子） 10.1051/epjconf/202227109004	査読の有無 有
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1．著者名 Gubler Philipp、Bratkovskaya Elena、Song Taesoo	4．巻 274
2．論文標題 Phi meson properties in nuclear matter from dilepton spectra in a transport approach	5．発行年 2022年
3．雑誌名 EPJ Web of Conferences	6．最初と最後の頁 07015-(1～6)

掲載論文のDOI（デジタルオブジェクト識別子） 10.1051/epjconf/202227407015	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

〔学会発表〕　計29件（うち招待講演　10件／うち国際学会　22件）

1．発表者名 Gubler Philipp
2．発表標題 Phi meson properties in nuclear matter
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２．発表標題 Spectral modification of hadrons in nuclear matter
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４．発表年 2021年

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４．発表年 2021年

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２．発表標題 Proton nucleus transport simulations to study the origin of hadron masses
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２．発表標題 Studying the phi meson in nuclear matter by simulating pA reactions in a transport approach
３．学会等名 ELPH 研究会 C029「様々なフレーバー領域で探るクォーク・ハドロン多体系の分光と構造」
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２．発表標題 The phi meson in nuclear matter from dileptons - considering electromagnetic effects -
３．学会等名 Seminar at the Nuclear & Hadron Physics Group, Yonsei University（招待講演）（国際学会）
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〔図書〕　計0件

〔産業財産権〕

〔その他〕

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6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

8．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関