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研究課題名（和文）Strange and charm quarks in nuclear matter - connecting theory with experiment

研究課題名（英文）Strange and charm quarks in nuclear matter - connecting theory with experiment

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研究成果の概要（和文）：本プロジェクトの目的はストレンジ・クォーク及びチャーム・クォークがかかわる現象を通じて、強い相互作用に関する理解を深め、または非常に高温・高密度の物質におけるハドロン粒子の振る舞いを研究することであった。特に、ストレンジ・クォーク及び反ストレンジ・クォークから構成されるphi中間子の分散関係（エネルギーと運動量の関係）に焦点を当て、核物質においていかなる変更を受けるかを調べ、J-PARCのE16実験に対する予測を与えた。

研究成果の学術的意義や社会的意義
陽子、中性子、パイ中間子などのハドロン粒子の質量の大半がカイラル対称性の自発的破れの帰結として生成されことが予想される。しかし、この現象の実験的検証が未だにできていない。本研究では、ハドロン粒子の質量の起源を探るため、カイラル対称性が（部分的に）回復していると思われる高温・高密度の物質におけるハドロン粒子の振る舞いを研究している。特に、その実験的解明のための理論的な計算や数値シミュレーションなどを行っている。

研究成果の概要（英文）：The purpose of this research project was to deepen our understanding of the strong interaction and to study the behavior of hadrons in extremely hot and/or dense environments, by making use of phenomena related to strange and charm quarks. Special focus was laid on the dispersion relation (the relation between energy and momentum) of the phi meson, which is composed of a strange and anti-strange quark. The modification of this dispersion relation in nuclear matter was studied, providing a prediction for the E16 experiment at J-PARC.

研究分野：ハドロン物理学

キーワード：ストレンジ・クォーク　チャーム・クォーク　カイラル対称性　分散関係　phi中間子

１．研究開始当初の背景

The original background of this research project was the existence and usefulness of the strange (s) and charm (c) quark flavors [which are much heavier than the lighter and more abundant up (u) and down (d) quarks] for helping us to deepen our understanding of the strong interaction (Quantum ChromoDynamics: QCD) and to study the behavior of matter in extremely hot and/or dense environments. This can be done by making use of the novel phenomena, related mainly to hadrons involving s and c quarks. To study such phenomena, strong collaborations between theoretical and experimental researchers are indispensable. Especially the experimental research facility J-PARC at Tokai-mura is playing an important role for this project, as many of the experimental research related to it are conducted there. The principal investigator of this KAKENHI project therefore was planning to conduct his research while maintaining regular contact with the experimentalists at J-PARC. This was easy to implement, because the principal investigator moved to the Advanced Science Research Center (ASRC) at the Japan Atomic Energy Agency (JAEA), which is located in the same premises at the J-PARC facility and moreover has a strong experimental hadron physics group with is closely involved with the experiments related to this research project.

２．研究の目的

The original purposes of this research project will be described below, irrespective of whether they were later pursued in the actual research activity.

(1) Study the ϕ meson spectral function with finite momentum in nuclear matter and make predictions for the E16 experiment at J-PARC

The behavior of the ϕ meson in nuclear matter is currently being studied experimentally in the E16 experiment at J-PARC. One goal of this experiment is to study potential modifications of the dispersion relation (relation between its energy and momentum) of this particle in nuclear matter compared to free space. One purpose of the theoretical research project described in this report, was to study the same dispersion relation from a theoretical point of view and to provide some kind of theoretical prediction for the E16 experiment

(2) Explore the possibility of a strangelet from a first principle lattice QCD calculation

Strangelets are quark clusters containing roughly equal numbers of u, d and s quarks. They were conjectured already a long time ago, but have so far neither been observed in an actual experiment, nor been studied in a first-principle lattice QCD calculation. The second goal of this research proposal was to explore whether is it possible to investigate such a state with state-of-the-art lattice QCD methods.

(3) Find relations between the behavior of heavy-light mesons at finite density and the restoration of chiral symmetry in nuclear matter

Heavy-light (for instance D or B) mesons have attracted interest because they only have one light (u or d) quark, which moves around an almost static c (or b) quark. They can therefore be expected to be especially sensitive to the intrinsic properties of light quarks. The light quarks are strongly influenced by the properties of the chiral symmetry of the system that one is considering, which gives these quarks (at low density or temperature) a large constituent mass. Therefore, if a heavy-light meson mass changes in nuclear matter, this can be a signal for the partial restoration of chiral symmetry. The third goal of this research project was to provide quantitative relations between the heavy-light meson masses and chiral symmetry, for multiple mesonic channels, which could provide experimentalists with hints which observable might be most sensitive to the properties of chiral symmetry in nuclear matter.

３．研究の方法

The methods used in the actual research related to this project are described below.

(1) QCD sum rules
The method of QCD sum rules connects certain integrals of hadronic spectral functions to so-called QCD condensates, which among other features describe the realization of chiral symmetry of a specific state under consideration. It is therefore an ideal tool to study the relations between hadronic properties in hot or dense environments, with more fundamental characteristics of QCD. It is especially useful for studying hadrons in dense matter (such as nuclear matter), which is still difficult to do, using lattice QCD.

(2) Lattice QCD
Lattice QCD can by now be considered to be the most powerful tool to study hadrons and their properties from the first principles of QCD. For studying hadrons in vacuum or at finite temperature, the uncertainties of the method are by now so well under control, that calculations of many hadronic ground state properties are possible with a precision of only a few percent.

４．研究成果

In this section, I will describe the physics results that were obtained during the running time of this research project. I will furthermore discuss the modifications that were made to the initial research plans of the project.

(1) The ϕ meson spectrum with non-zero momentum in nuclear matter
The ϕ meson is a particle made from a strange quark and an anti-strange quark. It is considered to be an ideal probe to study the modifications of hadrons in nuclear matter, because it can decay into di-leptons (for instance, an electron and a positron), which do not feel the strong interaction and whose movement is hence not strongly disturbed due to the surrounding strongly interacting matter. To experimentally investigate its behavior in nuclear matter, the ϕ meson was/is in the KEK E325 and J-PARC E16 experiments produced inside of nuclei using proton-nucleus collisions. The ϕ mesons that are produced with a momentum of the order of 1 GeV in the lab frame (nuclei at rest). In most theoretical calculations that were done so far, the ϕ meson was however assumed to be at rest in nuclear matter. To make an accurate comparison between theory and experiment, the effect of non-zero momentum therefore should be taken into account.
This was the motivation to start a study of the ϕ meson spectrum with non-zero momentum in nuclear matter, which led to the paper published in Ref.[1]. In this work, we employ the method of QCD sum rules, which can be applied both to the zero momentum and non-zero momentum cases. One important effect of the finite momentum in nuclear matter is the splitting of the ϕ meson polarization modes into longitudinal and transverse components. While degenerate in vacuum, these modes behave differently in (hot and/or dense) matter due to the breaking of Lorentz symmetry (in other words, the existence of the special rest frame of the surrounding matter). In QCD sum rules, this splitting is caused by the emergence of Lorentz-violating (e.g. non-scalar) condensates. We here only show the final results, illustrated in Fig.1, where the masses corresponding to the two polarizations modes are shown as functions of momentum. It is observed that the two modes move away from each other approximately as quadratic functions of the momentum |q|. In an actual experiment which does not observe the angular distribution of the di-leptons, the longitudinal and transverse modes cannot be measured separately, but only their sum. Keeping in mind that there are two (degenerate) transverse modes and only one longitudinal

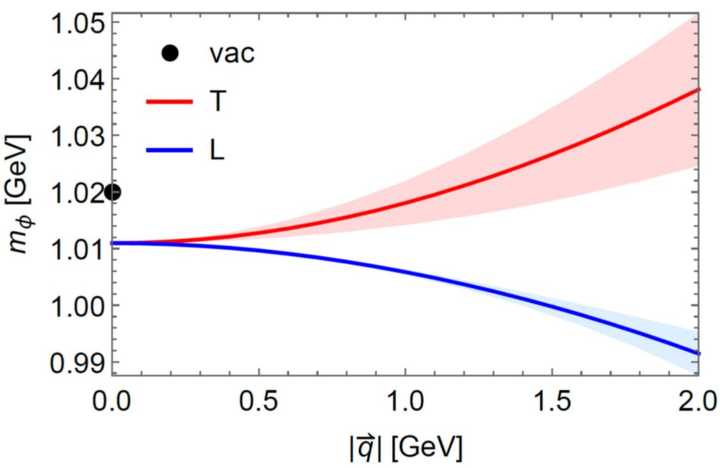

Fig. 1 The φ meson mass, shown as a function of momentum |q| for longitudinal (blue curve) and transverse (red curve) modes, at normal nuclear matter density. Adapted from Ref.[1].

mode, the measured momentum dependence will be a weighted average of the two, somewhat tilted to the side of the transverse mode.
The results of this work provide a prediction for the J-PARC E16 experiment, which plans to measure the momentum dependence of the ϕ meson mass in nuclear matter.

(2) Study of the strangelet making use of lattice QCD

After considering the possibility of studying a strangelet particle within a first principle lattice QCD approach, I realized that at the present stage, it would likely still be very difficult to obtain any reliable result with this method. Especially, the issue of the small signal-to-noise ratio for an increasing number of quarks, will make it a punishingly hard task to study particles with baryon numbers of three or larger. I have therefore decided to postpone this part of the project to a later time, and instead to focus on particles with a smaller number of quarks, that can be studied more easily.
I have hence joined a collaboration that studied the excited state spectrum of baryons containing at least one heavy quark, which led to the publication of Ref.[2]. Specifically, we studied the ground and first few excited states of the spin-1/2 and spin-3/2, singly, doubly, and triply charmed baryons. As a result, we identified several states that lie close to the experimentally observed excited states of the Σ_c, Ξ_c and Ω_c baryons, including some of the Ξ_c states recently reported by LHCb. Furthermore, we have started a new collaboration with the goal of studying exotic multiquark states on the lattice and using the quark model, which has so far resulted in two publications studying both pentaquark and tetraquark states in a quark model (Refs.[3,4]). Preparations for a lattice QCD study of exotic pentaquark states are currently underway.

(3) Study of heavy-light mesons in nuclear matter

While the initial plan of this project involved the study of heavy-light mesons in nuclear matter, I realized through discussions with collaborators, that while the study of such mesons in nuclear matter will be important especially for future experimental efforts, the study of their behavior in hot (instead of dense) matter is more relevant for currently ongoing experiments, especially high-energy heavy-ion collision experiments. I have therefore initiated a new collaborative project with researchers from Germany and South-Korea, studying the behavior of D-mesons at finite temperature and their relation to the potential melting behavior of the J/ψ-particle in the quark-gluon plasma, resulting in two publications (Refs.[5,6]).
In these works, we especially found that it is possible to relate the properties of the D-mesons at finite temperature to the heavy quark – anti-quark potential that is used to describe the J/ψ state (Ref.[5]). Furthermore, with the results of Ref.[5], it was then possible to study both the mass and the decay width of the J/ψ around the formation temperature of the quark-gluon plasma (Ref.[6]).

(4) Numerical simulations of the proton-nucleon reactions used to study the φ meson in nuclear matter

As a new direction of research, which was not foreseen at the time of the writing of the grant proposal, I started a new line of work in collaboration with researchers from Germany, with the goal of numerically simulating the proton-nucleon reactions measured at the E325 and E16 experiments at KEK and J-PARC. The motivation for carrying out these simulations is to make realistic comparisons between the data extracted from these experiments and the results of theoretical calculations. For this purpose, we make use of the PHSD transport approach, which is a microscopic off-shell transport approach for the description of strongly interacting hadronic and partonic matter in and out of equilibrium. It especially allows to incorporate the spectral function of the ϕ meson (as well as other vector mesons) and its density-dependence into the simulation, which makes it possible to compare various scenarios involving different spectral modifications with the experimental data.
This research project it currently still ongoing and has so far resulted in a number of conference proceedings which describe some preliminary results (Refs.[7,8]).

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１．著者名	４．巻
Gubler Philipp	336
２．論文標題	５．発行年
Towards understanding the phi meson in nuclear matter with finite momentum	2019年
３．雑誌名	６．最初と最後の頁
Proceedings of Science	207, 1-6
掲載論文のDOI（デジタルオブジェクト識別子）	査読の有無
10.22323/1.336.0207	有
オープンアクセス	国際共著
オープンアクセスとしている（また、その予定である）	－

１．著者名	４．巻
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３．雑誌名	６．最初と最後の頁
Physics Letters B	135028, 1-8
掲載論文のDOI（デジタルオブジェクト識別子）	査読の有無
10.1016/j.physletb.2019.135028	有
オープンアクセス	国際共著
オープンアクセスとしている（また、その予定である）	該当する

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AIP Conference Proceedings	040015, 1-8
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10.1063/1.5118412	有
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掲載論文のDOI（デジタルオブジェクト識別子）	査読の有無
10.7566/JPSCP.26.022028	有
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オープンアクセスとしている（また、その予定である）	該当する

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３．雑誌名 JPS Conference Proceedings	６．最初と最後の頁 024023，1-5
掲載論文のDOI（デジタルオブジェクト識別子） 10.7566/JPSCP.26.024023	査読の有無 有
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２．論文標題 Numerical analytic continuation of Euclidean data	５．発行年 2019年
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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 該当する

１．著者名 Gubler Philipp、Satow Daisuke	４．巻 106
２．論文標題 Recent progress in QCD condensate evaluations and sum rules	５．発行年 2019年
３．雑誌名 Progress in Particle and Nuclear Physics	６．最初と最後の頁 1～67
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.ppnp.2019.02.005	査読の有無 有
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What can be measured at the E16 experiment at J-PARC?

３．学会等名
Korea-Japan Joint Workshop on the Present and the Future in Hadron Physics at J-PARC（招待講演）（国際学会）

４．発表年
2018年～2019年

１．発表者名 Gubler Philipp
２．発表標題 The phi meson in nuclear matter and the strangeness content of the nucleon
３．学会等名 Colloquium at the Physics Department of Yonsei University（招待講演）
４．発表年 2018年～2019年

〔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