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学 位 論 文 題 目	Structure Functions of Pion and Deuteron
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(Form 3)

Summary of Doctoral Thesis

Name in full Qin-Tao Song

Title Structure Functions of Pion and Deuteron

Structure functions of the pion and the deuteron are studied in this thesis. The first topic is on tensor-polarized parton distributions of the deuteron and their relation to a spin asymmetry in the proton-deuteron Drell-Yan process. The second topic is on generalized distribution amplitudes in the two-photon process $\gamma^*\gamma\rightarrow\pi^0\pi^0$. The third topic is on gluon transversity of the deuteron and its relation to the prompt-photon production cross section in the proton-deuteron collision.

First, in comparison with the spin-1/2 proton, there are additional spin observables for the deuteron because of its spin-1 nature, and they are tensor-polarized structure functions. In 2005, the HERMES collaboration observed the tensor structure function b_1 in the deep inelastic scattering (DIS) process with a polarized deuteron, and this measurement is not consistent with the standard deuteron prediction. Furthermore, there was an interesting indication that a finite antiquark tensor polarization exists. These results indicate that the structure function b_1 could probe an interesting new aspect in the deuteron. In the near future, b_1 will be accurately measured at Thomas Jefferson National Accelerator Facility (JLab), and the Drell-Yan experiment is now under consideration at Fermi National Accelerator Laboratory (Fermilab) by using the unpolarized proton beam and tensor-polarized deuteron target. The tensor-polarized antiquark distributions are not easily determined from the charged-lepton DIS; however, they can be measured in a proton-deuteron Drell-Yan process with the tensor-polarized deuteron target. In this work, we provide theoretical predictions for the spin asymmetry of the Fermilab Drell-Yan experiments by using optimum tensor-polarized parton distribution functions (PDFs) to explain the HERMES measurement. We find that the asymmetry is typically a few percent, and our results were used for proposing the polarized proton-deuteron Drell-Yan measurement within the Fermilab-E1039 experiment. If it is measured, it could probe new hadron physics, and such studies could create an interesting field of high-energy spin physics.

Second, the 3-dimensional (3D) structure functions, generalized parton distributions (GPDs) and generalized distribution amplitudes (GDAs), contain information on form factors, PDFs, distribution amplitudes (DAs) and orbital-angular-momentum

contributions to the hadron spin. The GPDs provide us a way to solve the proton spin puzzle. The GPDs can be measured by the deeply virtual Compton scattering (DVCS), and we could also obtain GPDs by the s-t crossing from the GDAs. As for the GDAs, they can be measured by the two-photon process $\gamma^*\gamma \rightarrow$hadron + antihadron, which is possible at KEKB. For this two-photon process, the cross section can be calculated theoretically with the GDAs of the hadron. One can obtain the GDAs by analyzing the experimental cross sections with a reasonable parameterization of the GDAs. In 2016, the Belle collaboration reported a measurement for the differential cross sections on $\gamma^*\gamma \rightarrow \pi^0\pi^0$ in e^+e^- collision. In this work, we obtained the pion GDAs by analyzing the Belle data. Moreover, we investigated matrix elements of the energy-momentum tensor and the gravitational form factors by using the obtained GDAs. The three-dimensional gravitational radii were calculated as 0.32-0.39 fm for mass radius and 0.82-0.88 fm for the mechanical radius. We found that the mass radius is smaller than the pion charge radius (0.659±0.004 fm, taken from PDG 2018) and that the mechanical radius is slightly bigger than the charge radius. At this stage, the errors of the Belle measurements are large. However, the precise measurements of $\gamma^*\gamma \rightarrow$hadron + antihadron are expected in the near future, since the Belle II collaboration just started taking data with a much higher luminosity of the Super KEKB in 2019. The GDAs are related to form factors of the energy-momentum tensor. These form factors are called gravitational form factors because matrix elements of the energy-momentum tensor are source of gravity. Therefore, it is very interesting to study the gravitational form factors, which contain mass, pressure, and shear-force distributions for hadrons, by obtaining accurate GDAs.

Third, the gluon transversity does not exist in the spin-1/2 nucleons; however, one can study the gluon transversity in the spin-1 hadrons such as deuteron and ρ meson. The gluon transversity is a leading-twist distribution function which needs the helicity flip of a hadron with spin more than one, for example, the deuteron. It is a very important new quantity to probe the transverse spin structure of hadrons by using the deuteron. The deuteron is a bound state of proton and neutron. Since the nucleons themselves do not contribute directly to the gluon transversity due to their spin-1/2 nature, the gluon transversity could be very small in the deuteron. If a finite gluon transversity will be found experimentally, it reflects a new aspect inside the deuteron. At present, the only possible experimental measurement of the gluon transversity is the electron-deuteron DIS at JLab. There is no study to measure it in the proton-deuteron collision, for example, at Fermilab. In this work, we propose that one can use the prompt-photon production process to obtain the deuteron gluon transversity. However, we find that the measurement of this process is not easy at this stage, since it is proportional to the twist-3 effect in the proton part together with helicity observation of the photon.

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Results of the doctoral thesis screening

博士論文審査結果

Name in Full
氏 名　Qin-Tao Song

Title
論文題目　Structure Functions of Pion and Deuteron

出願者の研究は、π中間子と重陽子の構造関数に関するものである。
重陽子のテンソル偏極分布関数は、陽子と中性子が互いに束縛されることで初めて現れる量で、テンソル偏極スピン非対称度を通して調べることができる。これまでに HERMES 実験で得られた深部非弾性散乱の構造関数 b_1 の実験結果は従来の予想よりも大きく、注目を集めている。申請者はこの実験結果を説明するパートン分布関数を用いて陽子・重陽子ドレル・ヤン過程のスピン非対称度を計算し、この量が Fermilab E1039 において測定可能であることを指摘した。また、重陽子のグルーオン・トランスバーシティと呼ばれる横偏極分布関数を、偏極陽子・重陽子反応を用いた光子生成で測定できることを示した。
ハドロンの構造関数である一般化分布関数（GDA）は、２光子過程 $\gamma^*\gamma \to h\,\bar{h}$ を通じて観測することができる。申請者は、π中間子２光子過程 $\gamma^*\gamma \to \pi^0\pi^0$ に対する Belle の実験データを利用して GDA を決定した。これによりπ中間子のテンソル形状因子と半径を計算し、質量半径が 0.32-0.39 fm, 力学的半径が 0.82-0.89 fm という結果を得た。

審査会における出願者の発表は、明確にわかりやすくまとめられていた。重陽子のテンソル構造関数のレヴュー及びスピン非対称度の計算結果を説明し、次にグルーオン横偏極度が陽子・重陽子反応における光子生成により決定できることを示した。最後に、π中間子２光子過程 $\gamma^*\gamma \to \pi^0\pi^0$ の断面積と GDA の定式化、Belle データの解析による GDA の決定について説明した。また、質問についても的確に対応した。

これらの成果はすでに Physical Review D 誌に２編の論文として発表されており、博士論文として必要な水準を満たしている。また、８編のプロシーデングを発表し、１３件の国際研究会口頭発表を行った。本論文は、Song 氏の学識と高い研究能力を示しており、審査員全員一致で博士論文審査を合格とした。