
I have been working on theoretical hadron and nuclear physics. I explain my major research results in order from the most recent one. References are cited from the publication list [1–78].

1. Equation-of-motion and Lorentz-invariance relations for PDFs of spin-1 hadrons

   Structure functions of polarized spin-1 hadrons will be measured at various accelerator facilities in the near future. Recently, transverse-momentum-dependent and collinear parton distribution functions were theoretically proposed at twist 3 and twist 4 [6] in addition to the twist-2 ones, so that full investigations became possible for structure functions of spin-1 hadrons in the same level with those of the spin-1/2 nucleons. Furthermore, twist-3 tensor-polarized multiparton distribution functions were also found recently for spin-1 hadrons [6]. In this work [1], we derived relations among the tensor-polarized distribution functions and twist-3 multiparton distribution functions defined by the field tensor from the equation of motion for quarks. We found the relations (1) for the twist-3 PDF f_{LT}, the trasverse-momentum moment PDF $f_{1LT}^{(1)}$, and the multiparton distribution functions $F_{G,LT}$ and $G_{G,LT}$; (2) for the twist-3 PDF e_{LL}, the twist-2 PDF f_{1LL}, and the multiparton distribution function $H_{G,LL}^{\perp}$. Then, the Lorentz-invariance relation was obtained for relating f_{LT}, $f_{1LT}^{(1)}$, f_{1LL}, and $F_{G,LT}$. In deriving these relations, we also found new relations among the multiparton distribution functions defined by the field tensor [$F_{D,LT}(x,y)$, $G_{D,LT}(x,y)$, $H_{D,LL}^{\perp}(x,y)$, $H_{D,TT}(x,y)$] and the ones defined by the covariant derivative [$F_{G,LT}(x,y)$, $G_{G,LT}(x,y)$, $H_{G,LL}^{\perp}(x,y)$, $H_{G,TT}(x,y)$]. These relations are valuable in constraining the distribution functions and learning about multiparton correlations in spin-1 hadrons.

2. Twist-2 relation and sum rule for parton distribution functions of spin-1 hadrons

   Sum rules for structure functions and their twist-2 relations have important roles in constraining their magnitudes and x dependencies and in studying higher-twist effects. The Wandzura-Wilczek (WW) relation and the Burkhardt-Cottingham (BC) sum rule are such examples for the polarized structure functions g_1 and g_2. Recently, new twist-3 and twist-4 parton distribution functions were proposed for spin-1 hadrons, so that it became possible to investigate spin-1 structure functions including higher-twist ones. We show in this work that an analogous twist-2 relation and a sum rule exist for the tensor-polarized parton distribution functions f_{1LL} and f_{LT}, where f_{1LL} is a twist-2 function and f_{LT} is a twist-3 one [3]. Namely, the twist-2 part of f_{LT} is expressed by an integral of f_{1LL} (or b_1) and the integral of the function $f_{2LT} = (2/3) f_{LT} - f_{1LL}$ over x vanishes. If the parton-model sum rule for f_{1LL} (b_1) is applied by assuming vanishing tensor-polarized antiquark distributions, another sum rule also exists for f_{LT} itself. These relations should be valuable for studying tensor-polarized distribution functions of spin-1 hadrons and for separating twist-2 components from higher-twist terms, as the WW relation and BC sum rule have been used for investigating x dependence and higher-twist effects in g_2. In deriving these relations, we indicate that four twist-3 multiparton distribution functions F_{LT}, G_{LT}, $H_{LL}^{\perp}$, and H_{TT} exist for tensor-polarized spin-1 hadrons. These multiparton distribution functions are also interesting to probe multiparton correlations in spin-1 hadrons. In the near future, we expect that physics of spin-1 hadrons will become a popular topic, since there are experimental projects to investigate spin structure of the spin-1 deuteron at the Jefferson Laboratory, the Fermilab, the nuclotron-based ion collider facility, the electron-ion colliders in US and China in 2020's and 2030's.

3. Science Requirements and Detector Concepts for the Electron-Ion Collider

   This report describes the physics case, the resulting detector requirements, and the evolving detector concepts for the experimental program at the Electron-Ion Collider (EIC) [4]. The EIC will be a powerful new high-luminosity facility in the United States with the capability to collide high-energy electron beams with high-energy proton and ion beams, providing access to those regions in the nucleon and nuclei where their structure is dominated by gluons. Moreover, polarized beams in the EIC will give unprecedented access to the spatial and spin structure of the proton, neutron, and light ions. The studies leading to this document were commissioned and organized by the EIC User Group with the objective of advancing the state and detail of the physics program and developing detector concepts that meet the emerging requirements in preparation for the realization of the EIC. The effort aims to provide the basis for further development of concepts for experimental equipment best suited for the science needs, including the importance of two complementary detectors and interaction regions. This report consists of three volumes. Volume I is an executive summary of our findings and developed concepts. In Volume II we describe studies of a wide range of physics measurements and the emerging requirements on detector acceptance and performance. Volume III discusses general-purpose detector concepts and the underlying technologies to meet the physics requirements. These considerations will form the basis for a world-class experimental program that aims to increase our understanding of the fundamental structure of all visible matter.

   In this report [4], S. Kumano contributed especially to the section of “7.5.2, Neutrino physics” for explaining the synergy between neutrino projects and EIC physics by discussing, 1. cross sections and kinematical regions, 2. studies of neutrino-nucleus interactions, 3. measurements of the strangeness content of the nucleon, 4. isospin physics and sum rules, 5. electroweak measurements and the NuTeV anomaly, and 6. possible GPD measurements in neutrino scattering.

4. Gluon content of proton and deuteron at NICA SPD

   The Spin Physics Detector (SPD) is a future multipurpose experiment foreseen to run at the Nuclotron-based Ion Collider fAcility (NICA), which is currently under construction at the Joint Institute for Nuclear Research (JINR, Dubna, Russia). The physics program of the experiment is based on collisions of longitudinally and transversely polarized protons and deuterons at $\sqrt{s}$ up to 27 GeV and luminosity up to 10^{32} cm^{-2} s^{-1}. The SPD will operate as a universal facility for comprehensive study of unpolarized and polarized gluon content of the nucleon, using different complementary probes such as: charmonia, open charm, and prompt photon production processes. The purpose of this work [5] is to make a thorough review of the physics objectives that can potentially be addressed at the SPD, underlining related theoretical aspects and discussing relevant experimental results when available. Among different pertinent phenomena, particular attention is drawn to the study of the gluon helicity, gluon Sivers and Boer-Mulders functions in the nucleon, as well as the gluon transversity distribution in the deuteron, via the measurement of specific single and double spin asymmetries.

   In this paper [5], S. Kumano contributed especially to the sections of “5.3 Gluon transversity in deuteron” and “5.4 Tensor-polarized gluon distribution in deuteron”. Since the NICA will have a polarized-deuteron beam, it is possible to investigate polarized structure functions, which are specific to the spin-1 deuteron. There exists the gluon transversity in the deuteron, whereas it does not exist in the spin-1/2 nucleon because the helicity flip

$\Delta s = 2$ is not possible. The deuteron is a bound state of a proton and a neutron; however, they cannot contribute directly to the gluon transversity of the deuteron. Therefore, the gluon transversity is an appropriate observable to find new hadronic physics beyond the simple bound system of the nucleons. The tensor-polarized structure functions are additional structure functions in the spin-1 deuteron to the ones of the spin-1/2 nucleon. They are valuable in shedding light on a new aspect of high-energy spin physics. Since the conventional convolution description does not agree with the existing HERMES data on the tensor-polarized structure function b_1 [11], they could be good quantities to find an exotic hadronic effect. These new observables will be investigated at NICA by direct-photon, J/ψ, and other hadron production process with the polarized-deuteron beam.

5. Transverse-momentum-dependent parton distribution functions for spin-1 hadrons

   We showed possible transverse-momentum-dependent parton distribution functions (TMDs) for spin-1 hadrons including twist-3 and 4 functions in addition to the leading twist-2 ones by investigating all the possible decomposition of a quark correlation function in the Lorentz-invariant way [6]. The Hermiticity and parity invariance were imposed in the decomposition; however, the time-reversal invariance was not used due to an active role of gauge links in the TMDs. Therefore, there exist time-reversal odd functions in addition to the time-reversal even ones in the TMDs. We listed all the functions up to twist-4 level because there were missing terms associated with the lightcone vector n in previous works on the twist-2 part and there was no correlation-function study in the twist-3 and 4 parts for spin-1 hadrons. We showed that 40 TMDs exist in the tensor-polarized spin-1 hadron in the twist 2, 3, and 4. Some expressions of twist-2 structure functions are modified from previous derivations due to the new terms with n, and we found 30 new structure functions in the twist 3 and 4 in this work. Since time-reversal-odd terms of the collinear correlation function should vanish after integrals over the partonic transverse momentum, we obtained new sum rules for the time-reversal-odd structure functions, $\int d^2k_T g_{LT} = \int d^2k_T h_{LL} = \int d^2k_T h_{3LL} = 0$. In addition, we indicated that new transverse-momentum-dependent fragmentation functions exist in tensor-polarized spin-1 hadrons. The TMDs are rare observables to find explicit color degrees of freedom in terms of color flow, which cannot be usually measured because the color is confined in hadrons. Furthermore, the studies of TMDs enable not only to find three-dimensional structure of hadrons, namely hadron tomography including transverse structure, but also to provide unique opportunities for creating interesting interdisciplinary physics fields such as gluon condensates, color Aharonov-Bohm effect, and color entanglement. The tensor structure functions may not be easily measured in experiments. However, high-intensity facility such as the Thomas Jefferson National Accelerator Facility (JLab), the Fermilab Main Injector, and future accelerators like electron-ion collider (EIC) may probe such observables. In addition, since the Nuclotron-based Ion Collider fAcility (NICA) focuses on spin-1 deuteron structure functions, there is a possibility to study the details of polarized structure functions of the deuteron at this facility.

6. Gluon transversity in polarized proton-deuteron Drell-Yan process

   Nucleon spin structure functions have been investigated mainly by longitudinally-polarized ones for finding the origin of the nucleon spin. Other types of spin structure functions are transversely-polarized ones. In particular, quark transversity distributions in the nucleons have very different properties from the longitudinally-polarized quark distribution functions, especially in scaling violation, because they are decoupled from the gluon transversity, due to the fact that they are helicity-flip, namely chiral-odd, distributions. Such studies are valuable for finding not only the origin of the nucleon spin but also a signature on physics beyond the standard model, because the electric dipole moment of the neutron is proportional to the transversity distributions. Now, there is experimental progress on the quark transversity distributions; however, there is no experimental information on gluon transversity. In fact, the gluon transversity does not exist for the spin-1/2 nucleons due to the helicity-conservation constraint. One needs a hadron with spin more than or equal to one, so that the helicity flip of two units is allowed. A stable spin-1 target is, for example, the deuteron for studying the gluon transversity.

In our work, we proposed a possibility for finding the gluon transversity at hadron-accelerator facilities, especially in the proton-deuteron Drell-Yan process with the linearly-polarized deuteron, by showing theoretical formalism and numerical results [7,8]. In the experiment, the information on the dimuon angular distribution is necessary in the final state; however, the proton beam does not have to be polarized. We showed the dependencies of the Drell-Yan cross section on the dimuon-mass squared $M_{\mu\mu}^2$, the dimuon transverse-momentum q_T, the dimuon rapidity y in the center-of-momentum frame, and the magnitude of the gluon transversity $\Delta_T g$. We also showed typical spin asymmetries in the Drell-Yan process. The gluon transversity is not experimentally measured; however, there are future experimental projects to measure them at Thomas Jefferson National Accelerator Facility (JLab) and Electron-Ion Collider (EIC). Therefore, much progress is expected for the gluon transversity in the near future. On the other hand, independent experiments are desirable at other experimental facilities, especially at hadron accelerator facilities, to probe different kinematical regions of the gluon transversity from the JLab and EIC ones. There are available hadron facilities at Fermilab, J-PARC (Japan Proton Accelerator Research Complex), GSI-FAIR (Gesellschaft für Schwerionenforschung -Facility for Antiproton and Ion Research), and NICA (Nuclotron-based Ion Collider fAcility). In addition, if the fixed-deuteron target becomes possible at RHIC, Large Hadron Collider (LHC), or EIC, there could be a possibility. We showed in our studies that the gluon transversity could be investigated by the proton-deuteron Drell-Yan process with the linearly-polarized deuteron. This experiment is under consideration in the Fermilab-E1039 project. Since the internal spin-1/2 nucleons within the deuteron cannot contribute directly to the gluon transversity, it could be a good observable to find a new non-nucleonic component beyond the simple bound system of nucleons in nuclei.

7. Gravitational form factors of hadrons

The nucleon spin used to be explained by a combination of three-quark spins in the nucleon according to the basic quark model. However, it became clear that the quark contribution to the nucleon spin is 20−30%, and the rest of spin should come from gluon-spin and partonic orbital-angular-momentum (OAM) contributions. For finding the OAM part, it became necessary to investigate three-dimensional structure of the nucleon, including transverse structure in addition to the longitudinal one described by the Bjorken variable x. This field is called hadron tomography. It can be investigated by three-dimensional structure functions such as generalized parton distributions (GPDs), transverse-momentum-dependent parton distributions, and generalized distribution amplitudes (GDAs).

In our work, we extracted the GDAs, which are s-t crossed quantities of the GPDs, from cross-section measurements of hadron-pair production process $\gamma^*\gamma \to \pi^0\pi^0$ at KEKB [9,10]. This work was the first attempt to obtain the GDAs and gravitational form factors from the actual experimental data. The GDAs were expressed by a number of parameters and they were determined from the data of $\gamma^*\gamma \to \pi^0\pi^0$ by including intermediate scalar- and tensor-meson contributions to the cross section. Our results indicated that the dependence of parton-momentum fraction z in the GDAs is close to the asymptotic one. The timelike gravitational form factors Θ_1 and Θ_2 were obtained from our GDAs, and they were converted to the spacelike ones by the dispersion relation. To be precise, they are the form factors of energy-momentum tensors in QCD; however, they are often called gravitational form factors in hadron physics. From the spacelike Θ_1 and Θ_2, gravitational densities of the pion were calculated. Then, we obtained the mass (energy) radius and the mechanical (pressure and shear force) radius from Θ_2 and Θ_1, respectively. They were calculated as $\sqrt{\langle r^2 \rangle_{\text{mass}}} = 0.32 \sim 0.39$ fm, whereas the mechanical radius was larger $\sqrt{\langle r^2 \rangle_{\text{mech}}} = 0.82 \sim 0.88$ fm. This is the first report on the gravitational radius of a hadron from actual experimental measurements [10]. It is interesting to find the possibility that the gravitational mass and mechanical radii could be different from the experimental charge radius $\sqrt{\langle r^2 \rangle_{\text{charge}}} = 0.672 \pm 0.008$ fm for the charged pion.

For drawing a clear conclusion on the GDAs of hadrons, accurate experimental data are needed, and it should be possible, for example, by future measurements of super-KEKB and international linear collider (ILC). Accurate measurements will not only provide important information on hadron tomography but also possibly shed light on gravitational physics in the quark and gluon level. Gravitational physics used to be considered as a field on macroscopic world. However, we showed that it is possible to investigate it in the microscopic level in terms of fundamental particles of quarks and gluons. In future, we expect much progress on origin of hadron masses and internal hadron pressures in terms of quark and gluon degrees of freedom. This work together with our studies on the gluon transversity was selected one of highlight research results of KEK in the annual report of 2019.

8. Tensor-polarized structure function b_1 in standard convolution description of deuteron

Tensor-polarized structure functions b_{1-4} of a spin-1 hadron are additional observables which do not exist for the spin-1/2 nucleons. They could probe novel aspects of the internal hadron structure. Twist-2 tensor-polarized structure functions are b_1 and b_2, and they are related by the Callan-Gross-like relation in the Bjorken scaling limit. The other functions b_3 and b_4 are higher-twist ones, which may not be easily accessed experimentally at this stage.

In this work, we theoretically calculated b_1 in the standard convolution description for the deuteron [11]. Two different theoretical models, a basic convolution description and a virtual nucleon approximation, were used for calculating b_1 and their results were compared with the HERMES measurement. The convolution model means that the deuteron structure function is evaluated by the nucleonic structure function convoluted with the nucleon momentum distribution in the deuteron. Namely, the virtual-photon interaction is split into two processes in the charged-lepton scattering with the deuteron. First, the nucleon momentum distribution within the deuteron is calculated, and then the photon interaction with a quark or an antiquark is calculated. The total effect is expressed by a convolution integral. The deuteron is mainly the S-wave bound state of proton and neutron; however, there is a small admixture of D wave. From this convolution description, the structure function b_1 of the deuteron was expressed by the structure functions F_1 for the nucleons with the tensor-polarization combination of the nucleon's lightcone-momentum distributions. There were an S-D interference contribution and a purely D-wave one for b_1. Estimating the convolution expression for b_1, we found large differences between our theoretical results and the data. In the measured x range ($x < 0.5$), the experimental magnitude was one-order larger than both theoretical estimates. Furthermore, there were relatively large distributions even at large x ($0.6 < x < 0.8$). Because the HERMES errors are large, we cannot draw a solid conclusion from this comparison. However, the large differences indicated that a new hadron physics mechanism could be possibly needed for their interpretation, although there are still some rooms to improve, for example, by considering higher-twist effects.

Future b_1 studies could shed light on this new field of hadron physics. In particular, detailed experimental studies of b_1 will start at the Thomas Jefferson National Accelerator Facility. In addition, there are possibilities to investigate tensor-polarized parton distribution functions and b_1 at Fermi National Accelerator Laboratory and a future electron-ion collider. Therefore, further theoretical studies are needed for understanding the tensor structure of the spin-1 deuteron, including a new mechanism to explain the large differences between the current data and our theoretical results.

9. Unified model of neutrino-nucleus reactions

   Neutrino oscillation experiments have been done for finding new physics beyond the standard model. Since nuclear targets are used in the experiments, for example water in the T2K project, a precise description of neutrino-nucleus reactions plays a key role in addressing fundamental questions such as the leptonic CP violation and the neutrino mass hierarchy through analyzing data on neutrino oscillation experiments. The neutrino energy relevant to the neutrino-nucleus reactions spans a broad range. Accordingly, the dominant reaction mechanism varies across the energy region from quasi-elastic scattering through nucleon resonance excitations to deep inelastic scattering. This corresponds to transitions of the effective degree of freedom for theoretical description from nucleons through meson-baryon to quarks.

   The main purpose of our review [12] was to report our recent efforts towards a unified description of the neutrino-nucleus reactions over the wide energy range, and recent overall progress in the field was also sketched. Starting with an overview of the current status of neutrino-nucleus scattering experiments, we formulated the cross section to be commonly used for the reactions over all the energy regions. At low energies with the momentum-transfer squared $Q^2 < 1$ GeV^2 and invariant-mass squared $W^2 < 4$ GeV^2, the reaction is described by quasi-elastic scattering with nucleons and by nucleon resonances. At high energies with $Q^2 > 1$ GeV^2 and $W^2 > 4$ GeV^2, it is described by deep inelastic scattering (DIS) with a nucleus in terms of quarks and gluons. In the region with $Q^2 < 1$ GeV^2 and $W^2 > 4$ GeV^2, the reaction is expressed by Reggeons and Pomerons by noting the partially conserved axial-vector current (PCAC) relation at $Q^2 \to 0$. We also noted the quark-hadron duality in connecting both resonance and DIS regions. These theoretical models were checked by experimental measurements of electron scattering, and the axial-vector terms were introduced for the neutrino reactions. A description of the neutrino-nucleon reactions followed and, in particular, a dynamical coupled-channels model for meson productions in and beyond the $\Delta(1232)$ region was discussed in detail. We then discussed the neutrino-nucleus reactions, putting emphasis on our theoretical approaches. We started the discussion with electroweak processes in few-nucleon systems studied with the correlated Gaussian method. Then, we described quasi-elastic scattering with nuclear spectral functions, and meson productions with a Δ-hole model. Nuclear modifications of the parton distribution functions determined through a global analysis were also discussed. Finally, we discussed issues to be addressed for future developments.

10. Global analyses of fragmentation functions

    Fragmentation functions indicate probabilities to find hadrons created from parent quarks or a gluon, and they are essential, for example, for calculating hadron-production cross sections in high-energy reactions in order to study the origin of nucleon spin, properties of quark-gluon plasma, and signatures beyond the standard model. In our studies, fragmentation functions and their uncertainties were determined for pion, kaon, and proton by a global χ^2 analysis of charged-hadron production data in electron-positron annihilation and by the Hessian method for error estimation [37]. It is especially important that the uncertainties of the fragmentation functions were estimated in this analysis for the first time. The results indicated that the fragmentation functions, especially gluon and light-quark fragmentation functions, had large uncertainties at small Q^2. We found that determination of the fragmentation functions is improved in next-to-leading-order (NLO) analyses for the pion and kaon in comparison with leading-order ones. Such a NLO improvement was not obvious in the proton. Since the uncertainties are large at small Q^2, the uncertainty estimation is very important for analyzing hadron-production data at small Q^2 or p_T (Q^2, $p_T^2 << M_Z^2$) in lepton scattering and hadron-hadron collisions. A code is available for general users for calculating obtained fragmentation functions.

    In 2013, accurate measurements were reported by the Belle and BaBar collaborations for the fragmentation functions at the center-of-mass energies of 10.52 GeV and 10.54 GeV, respectively, at the KEK and SLAC B factories, whereas other available e^+e^- measurements were mostly done at higher energies, mainly at the Z mass of 91.2 GeV. We reported our global analysis of the fragmentation functions especially to show impacts of the B-factory measurements on the fragmentation function determination [14]. Our results indicated that the fragmentation functions are determined more accurately not only by the scaling violation but also by high-statistical nature of the Belle and BaBar data. We also explained how the flavor dependence of quark fragmentation functions and the gluon function are separated by using measurements at different Q^2 values. In particular, the electric and weak charges are different depending on the quark type, so that a light-quark flavor separation also became possible in principle due to the precise data at both $\sqrt{s} \simeq 10.5$ GeV and 91.2 GeV.

    Next, we performed the first iterative Monte Carlo (IMC) analysis of fragmentation functions [13]. The IMC method eliminates potential bias in traditional analyses based on single fits introduced by fixing parameters not well constrained by the data and provides a statistically rigorous determination of uncertainties. Our analysis revealed specific features of fragmentation functions using the new IMC methodology and those obtained from previous analyses, especially for light quarks and for strange-quark fragmentation to kaons.

    Third, we proposed that fragmentation functions should be used to identify exotic hadrons by using properties of favored- and disfavored-fragmentation functions [35]. The favored fragmentation means a fragmentation from a quark or an antiquark which exists in a hadron as a constituent in a quark model, and the disfavored means a fragmentation from a sea quark. As an example, fragmentation functions of the scalar meson $f_0(980)$ were investigated. It was pointed out that the second moments and functional forms of the u- and s-quark fragmentation functions could distinguish the tetraquark structure from

$q\bar{q}$. By the global analysis of $f_0(980)$-production data in electron-positron annihilation, its fragmentation functions and their uncertainties were determined. It was found that the current available data are not sufficient to determine its internal structure, while precise data in future should be able to identify exotic quark configurations.

11. Tensor-polarization asymmetry in proton-deuteron Drell-Yan process

    Tensor-polarized parton distribution functions are new quantities in spin-one hadrons such as the deuteron, and they could probe new quark-gluon dynamics in hadron and nuclear physics. In charged-lepton deep inelastic scattering (DIS), they are studied by the twist-two structure functions b_1 and b_2. The HERMES collaboration found much larger $|b_1|$ values than a naive theoretical expectation based on the standard deuteron model. The situation should be significantly improved in the near future by an approved experiment to measure b_1 at JLab (Thomas Jefferson National Accelerator Facility). There was also an interesting indication in the HERMES result that finite antiquark tensor polarization exists $\int dx b_1(x) = [\,0.35 \pm 0.10\,(\text{stat}) \pm 0.18\,(\text{sys})\,]$, which indicates a deviation from the sum rule $\int dx b_1(x) = 0$ in Ref. [69]. This finite tensor polarization could play an important role in solving a mechanism on tensor structure in the quark-gluon level. The tensor-polarized antiquark distributions are not easily determined from the charged-lepton DIS such as the HERMES and JLab measurements; however, they can be measured in a proton-deuteron Drell-Yan process with a tensor-polarized deuteron target.

    In our work, we estimated the tensor-polarization asymmetry for a possible Fermilab Main-Injector experiment E1039 by using optimum tensor-polarized PDFs to explain the HERMES measurement [15]. The tensor-polarized PDFs at the HERMES kinematics ($Q^2 = 2.5$ GeV^2) [29] were evolved to the ones at the larger-Q^2 Fermilab region. We found that the asymmetry is typically a few percent. If it is measured, it could probe new hadron physics, and such studies could create an interesting field of high-energy spin physics. In addition, we found that a significant tensor-polarized gluon distribution should exist due to Q^2 evolution, even if it were zero at a low Q^2 scale. The tensor-polarized gluon distribution has never been observed, so that it is an interesting future project. Our formalism is valid not only for the Fermilab experiment but also for any other hadron facilities such as J-PARC, GSI-FAIR, and NICA. Furthermore, if the fixed-deuteron target becomes possible at RHIC, Large Hadron Collider (LHC), or EIC, our studies can be used.

12. GPD experiment by using pion-induced exclusive Drell-Yan process at J-PARC

    Generalized parton distributions (GPDs) encoding multidimensional information of hadron partonic structure appear as the building blocks in a factorized description of hard exclusive reactions. The nucleon GPDs have been accessed by deeply virtual Compton scattering and deeply virtual meson production with lepton beam. A complementary probe with hadron beam is the exclusive pion-induced Drell-Yan process.

    In our work, we discussed recent theoretical advances on describing this process in terms of nucleon GPDs and pion distribution amplitudes. In the framework of the J-PARC E50 experiment, we addressed the feasibility of measuring the exclusive pion-induced Drell-Yan process $\pi^- p \to \mu^+ \mu^- n$ in the coming high-momentum beam line of J-PARC [16]. Detailed simulations on signal reconstruction efficiency as well as on rejection of the most severe random background channel were performed for the pion beam momentum in the range of $10-20$ GeV. A clean signal of exclusive pion-induced Drell-Yan process can be identified in the missing-mass spectrum of dimuon events with $2-4$ fb^{-1} integrated luminosity. The statistics accuracy is adequate for discriminating between the predictions from two current GPD modelings. The realization of this measurement will represent not only a new approach of accessing nucleon GPDs and pion distribution amplitudes (DAs) in the timelike process, but also a novel test of the factorization of an exclusive Drell-Yan process associated with timelike virtuality and the universality of GPDs in spacelike and timelike processes. Since both inclusive and exclusive Drell-Yan events could be measured simultaneously, the data could reveal interesting features in the transition from inclusive Drell-Yan to the semi-exclusive and exclusive limits. The pion pole in the GPD $\tilde{E}$ is expected to give a dominant contribution in the cross sections at small $|t|$. The cross sections at this pion-pole dominance region will provide a unique opportunity to access the pion timelike form factor other than the approach of e^+e^- annihilation process. The input cross section used for the exclusive Drell-Yan events in this work was the prediction within the factorization approach using the partonic hard scattering in the leading order of α_s convoluted with the leading-twist pion DAs and nucleon GPDs. Realization of such measurement at J-PARC will provide a new test of perturbative QCD descriptions of a novel class of hard exclusive reactions. It is complementary to the JLab experiment in the sense that the J-PARC experiment will probe a different x region ($x = 0.1$-0.3) from the JLab one $x = 0.3$-0.6. It will also offer the possibility of experimentally accessing nucleon GPDs at large timelike virtuality. In 2019, a LoI (Letter of Intent) was submitted on this experiment by joining the J-PARC-E50 project, whose main topic is on charmed-baryon spectroscopy, in the high-momentum beamline.

13. Exotic hadron structure by constituent-counting rule for hard exclusive processes

A basic quark model indicates that baryons consist of three quarks (qqq) and mesons of a quark-antiquark pair ($q\bar{q}$). Hadrons with other compositions, such as $qq\bar{q}\bar{q}$ and $qqqq\bar{q}$, are exotic hadrons. After 2004, there have been several reports on exotic hadron candidates. However, it is not easy to confirm their exotic nature by global observables like masses, decay widths, and spins. Therefore, we proposed to use high-energy hadron reactions and perturbative QCD for finding internal structure of the exotic candidates to clarify the exotic nature [17,23]. According to perturbative QCD, exclusive high-energy hadron reactions occur by hard gluon exchanges. Therefore, their cross sections are estimated by considering hard quark and gluon propagators together with other kinematical factors. It leads to the so-called constituent counting rule which indicates, for example, that a two-body exclusive hadron reaction cross section $a + b \to c + d$ scales like $d\sigma/dt \sim f(\theta_{cm})/s^{n-1}$ with $n = n_a + n_b + n_c + n_d$, where n_i is the number of elementary constituents participate in the reaction and s is the center-of-mass energy squared. This theoretical prediction had been confirmed by BNL and JLab experiments.

We proposed to use hard exclusive production of an exotic hadron for finding its internal quark-gluon configuration by the constituent-counting rule in perturbative QCD. Especially, we investigated internal structure of hyperons and their excited states by using the high-momentum pion beam at J-PARC. First, the cross section for the exclusive process $\pi^- + p \to K^0 + \Lambda(1405)$ was estimated at the scattering angle $\theta = 90°$ in the center-of-mass frame by using current experimental data [23]. In comparison, the cross section for the ground-state Λ production $\pi^- + p \to K^0 + \Lambda$ was also shown. We suggested that the internal quark configuration of $\Lambda(1405)$ should be determined by the asymptotic scaling behavior of the cross section. If it is an ordinary three-quark baryon, the scaling of the cross section is $s^8 d\sigma/dt$ =constant, whereas it is $s^{10} d\sigma/dt$ =constant if $\Lambda(1405)$ is a five-quark hadron, where s and t are Mandelstam variables. Such a measurement will be possible, for example, by using the high-momentum beamline at J-PARC. In addition, another exclusive process $\gamma + p \to K^+ + \Lambda(1405)$ could be investigated at LEPS and JLab for finding the nature of $\Lambda\,(1405)$. We indicated that the constituent-counting rule could be used as a valuable observable in determining internal structure of exotic hadrons by high-energy exclusive processes, where quark-gluon degrees of freedom explicitly appear. Furthermore, it is interesting to investigate the transition from hadron degrees of freedom to quark-gluon ones for exclusive exotic-hadron production processes.

Second, we analyzed the JLab-CLAS data on the photoproduction of hyperon resonances, as well as the available data for the ground state Λ and Σ^0 of the CLAS and SLAC-E84 collaborations, by considering constituent-counting rule suggested by perturbative QCD [17]. From the analyses of the $\gamma\, p \to K^+\Lambda$ and $K^+\Sigma^0$ reactions, we found that the number of the elementary constituents is consistent with $n_\gamma = 1$, $n_p = 3$, $n_{K^+} = 2$, and $n_\Lambda = n_{\Sigma^0} = 3$. Then, the analysis was made for the photoproductions of the hyperon resonances $\Lambda(1405)$, $\Sigma(1385)^0$, and $\Lambda(1520)$, where $\Lambda(1405)$ could be considered to be a $\bar{K}N$ molecule and hence its constituent number could be five. However, we found that the current data are not enough to conclude the numbers of their constituent. It is necessary to investigate the higher-energy region at $\sqrt{s} > 2.8$ GeV experimentally beyond the energy of the available CLAS data for counting the number of constituents clearly. We also mentioned that our results indicate energy dependence in the constituent number, especially for $\Lambda(1405)$. Namely, $\Lambda(1405)$ looked like a penta-quark state at lower energies, but it became a three-quark one at high energies. If an excited hyperon is a mixture of three-quark and five-quark states, the energy dependence of the scaling behavior could be valuable for finding its composition and mixture. We expect to have much progress in future on the internal structure of exotic hadron candidates by using high-energy hadron reactions, as a new field on exotic hadrons.

14. Compositeness of exotic hadron candidates

In recent years, there are a number of reports on exotic hadron candidates. They are theoretically described by ordinary hadrons ($q\bar{q}$, qqq), exotic configurations, hadron molecules, or their mixtures. These models contain parameters which are adjusted to explain experimental observables, so that their descriptions are not necessarily appropriate ways to understand their internal structure. As a possible method to understand the hadron structure is to investigate compositeness of bound-state systems.

In our studies, structure of the $a_0(980)$ and $f_0(980)$ resonances was investigated with the $a_0(980)$-$f_0(980)$ mixing intensity from the viewpoint of compositeness [18], which corresponds to the amount of two-body states composing resonances as well as bound states. If it is one, the hadron is a bound state of a hadron molecule, and it is an ordinary hadron described by the basic quark model if the compositeness is zero. For example, since it is not possible to explain the strong decay width of $f_0 \to \pi\pi$ by quark models with the $q\bar{q}$ configuration [75] and also from experimental measurements on the radiative decay $\phi \to f_0\gamma$ [63] and the two-photon decay width ($f_0 \to \gamma\gamma$), $f_0(980)$ could be considered as a $K\bar{K}$ molecule.

For this purpose, we first formulated the $a_0(980)$-$f_0(980)$ mixing intensity as the ratio of two partial decay widths of a parent particle, in the same manner as the recent analysis in BES (Beijing Spectrometer) experiments. Calculating the $a_0(980)$-$f_0(980)$ mixing intensity with the existing Flatte parameters from experiments, we found that many combinations of the $a_0(980)$ and $f_0(980)$ Flatte parameters can reproduce the experimental value of the $a_0(980)$-$f_0(980)$ mixing intensity by BES. Next, from the same Flatte parameters, we also calculated the $K\bar{K}$ compositeness for $a_0(980)$ and $f_0(980)$. Although the compositeness with the correct normalization became complex in general for resonance states, we found that the Flatte parameters for $f_0(980)$ imply large absolute value of the $K\bar{K}$ compositeness and the parameters for $a_0(980)$ led to small but nonnegligible absolute value of the $K\bar{K}$ compositeness. Then, connecting the mixing intensity and the $K\bar{K}$ compositeness via the $a_0(980)$- and $f_0(980)$-$K\bar{K}$ coupling constants, we established a relation between them. As a result, a small mixing intensity indicated a small value of the product of the $K\bar{K}$ compositeness for the $a_0(980)$ and $f_0(980)$ resonances. Moreover, the experimental value of the $a_0(980)$-$f_0(980)$ mixing intensity implied that the $a_0(980)$ and $f_0(980)$ resonances cannot be simultaneously $K\bar{K}$ molecular states. These two results suggested a new viewpoint that $f_0(980)$ is mainly a $K\bar{K}$ state and $a_0(980)$ is an ordinary quark bound state, although both states used to be considered as $K\bar{K}$ states.

15. Achievements of B factories and their fragmentation-function measurements

The B factories at KEK and SLAC had investigated breaking of particle-antiparticle asymmetry and found new particles by using abundantly-produced B mesons, τ particles, and charmed mesons. At these facilities, significant achievements were done by finding the symmetry breading between B meson and anti-B meson and confirming the Kobayashi-Masukawa theory. In addition, they had important findings on exotic hadrons and precise measurements on fragmentation functions in hadron physics. In this report "The Physics of the B Factories" [19], these achievements were summarized as sections on accelerator facilities, analysis tools and methods, Kobayashi-Maskawa mechanism and its confirmation, hadron spectroscopy, fragmentation functions, and so on. This report was press released from KEK on July 11, 2014 as the "50 years since the discovery of CP symmetry breaking: Joint report of Belle and BaBar experiments for confirming the Kobayashi-Maskawa theory".

S. Kumano contributed especially to the explanations on fragmentation functions in this report. The fragmentation functions were measured mainly in the Z-mass region by the electron-positron annihilation at Large Electron-Positron Collider (LEP) and SLAC Large Detector (SLD). However, the Belle and BaBar collaborations reported very-precise data on the fragmentation functions in 2013 for light hadrons (π, K, $p/\bar{p}$). Furthermore, these data covered the wide kinematical region of the energy fraction z, which is the ratio of produced-hadron energy to the half of the center-of-mass energy, so that it became possible to determine the fragmentation functions accurately. These B-factory energies of about 10 GeV are much smaller than the Z-mass energy region of LEP and SLD, so that gluon fragmentation functions should be determined for the first time through the scaling violation. These studies contributed to other fields of physics, such as on properties of quark-gluon plasma in heavy-ion collisions and on origin of nucleon spin in polarized-proton reactions, because the fragmentation functions are necessary quantities for describing cross sections of semi-inclusive hadron productions. In addition, chiral-odd fragmentation-function measurements at the B factories made it possible to find the chiral-odd parton distributions and transverse-spin physics for clarifying the origin of the nucleon spin. The details of these B factory achievements were explained in Ref. [19].

16. Tomography of exotic hadrons in high-energy exclusive processes with GPDs and GDAs

    There are a number of reports on exotic hadrons in recent years; however, it is not clear whether they are really exotic ones from global observables such as masses and decay widths. As a new approach, we investigated the possibility of determining internal structure of exotic hadrons by using high-energy reaction processes [20], where quarks and gluons are appropriate degrees of freedom. In particular, it should be valuable to investigate the high-energy exclusive processes which include generalized parton distributions (GPDs) and generalized distribution amplitudes (GDAs). The GPDs and GDAs contain momentum distributions of partons and form factors. We found that the exotic nature appears in momentum distributions of quarks as suggested by the constituent-counting rule and in the form factors associated with exotic hadron sizes and the number of constituents.

    First, we showed that the valence-quark distributions of tetraquark ($n = 4$) and pentaquark ($n = 5$) hadrons shift to smaller-x regions from the distributions of the pion ($n = 2$) and the nucleon ($n = 3$). Here, n is the number of valence quarks. The x-dependent distributions were determined by the number of valence quarks and the momentum fraction carried by quarks. Second, the large-Q^2 behavior of form factors is given by the constituent counting rule of perturbative QCD, so that exotic nature should be found by looking at the high-momentum region of the hadron form factors. Since exotic hadrons are unstable particles, they cannot be used as fixed targets and the spacelike GPDs cannot be measured experimentally, although transition GPDs to exotic hadrons could probe such signatures. However, exotic hadrons can be investigated by timelike processes, as we proposed that these exotic signatures should be found in exclusive production processes of exotic hadrons from $\gamma^*\gamma$ in electron-positron annihilation. For example, the GDAs contain information on a time-like form factor of the energy-momentum tensor of a hadron h. We showed that the cross section of $e\gamma \to e + h\bar{h}$ is sensitive to the exotic signature by looking at the $h\bar{h}$ invariant-mass dependence by taking light hadrons, $h = f_0(980)$ and $a_0(980)$. From such GDA measurements, the tomography of exotic hadrons will become possible, for example, by Belle and BaBar experiments and by future linear collider [20].

17. Determination of $\Lambda(1405)$ compositeness from its radiative decay

    Nucleons, N^* resonances, and other baryons are generally described by the quark model with the qqq composition. However, the mass of $\Lambda(1405)$ is much different from experimental measurements, so that it is considered as a $\bar{K}N$ molecule state. Since new kaonic nuclei have been investigated at J-PARC and other facilities, the internal structure of $\Lambda(1405)$ should be clarified because it is possibly the simplest bound system of $\bar{K}N$. In our studies, the radiative decay of $\Lambda(1405)$ was investigated from the viewpoint of compositeness [21], which corresponds to the amount of two-body states composing resonances as well as bound states. This radiative decay is an E1 transition, which is described by the matrix element of the electric dipole operator $e\vec{r}$. It indicates that a diffuse molecular state or a compact quark-bound state could be distinguished by this E1 radiative decay. In particular, we investigated the compositeness of $\Lambda(1405)$ by this decay.

    For a $\bar{K}N(I = 0)$ bound state without couplings to other channels, we established a relation between the radiative decay width and the compositeness. Especially, the radiative decay width of the bound state is proportional to the compositeness. Applying the formulation to $\Lambda(1405)$, we observed that the decay to $\Lambda\gamma$ is dominated by the K^-p component inside $\Lambda(1405)$, because in this decay $\pi^+\Sigma^-$ and $\pi^-\Sigma^+$ strongly cancel with each other and the $\pi\Sigma$ component can contribute to the $\Lambda\gamma$ decay only through the slight isospin breaking. This means that the decay $\Lambda(1405) \to \Lambda\gamma$ is suitable for the study of the $\bar{K}N$ component in $\Lambda(1405)$. Fixing the $\Lambda(1405)$-$\pi\Sigma$ coupling constant from the usual decay of $\Lambda(1405) \to \pi\Sigma$, we showed a relation between the absolute value of the $\bar{K}N$ compositeness for $\Lambda(1405)$ and the radiative decay width of $\Lambda(1405) \to \Lambda\gamma$ and $\Sigma^0\gamma$, and we found that large decay width to $\Lambda\gamma$ implies large $\bar{K}N$ compositeness for $\Lambda(1405)$. The compositeness of $\pi\Sigma$ was estimated about 0.19, so that the $\pi\Sigma$ molecular composition is relatively small. By using the "experimental" data on the radiative decay widths based on an isobar-model fitting of the K^-p atom data, we estimated the $\bar{K}N$ compositeness for $\Lambda(1405)$. We also discussed the pole-position dependence of our relation on the $\Lambda(1405)$ radiative decay width and the effects of the two-pole structure for $\Lambda(1405)$. For a precise determination of the compositeness, we need to have an accurate measurement of the radiative decay width, which should be possible at J-PARC.

18. Report on future nuclear physics in Japan: Nucleon-structure physics

In the 21st century, world's leading accelerator facilities such as J-PARC, KEKB, and RIBF were completed in Japan. Together with RCNP and ELPH, it became possible to investigate diverse aspects of hadron and nuclear physics. In addition, there was significant progress on performance of super-computers. On the other hand, there are major accelerator facilities in the world such as CERN-LHC, CERN-COMPASS, RHIC, Fermilab, JLab, and GSI, and many Japanese scientists participate in these facility experiments. These experimental projects cover diverse fields of hadron and nuclear physics. Nuclear physicists devote to their own projects and there is a tendency that they may not pay attention to developments on other fields. In addition, more than 20 years had passed for the J-PARC and RIBF since the early planning stage, so that physics projects of these facilities should be re-examined. Therefore, by the proposal of the Japanese Nuclear Physics Executive Committee, we wrote a report on plans on future nuclear physics projects in 2013 [22] and showed possible direction of nuclear physics in Japan. This report covered a wide range of hadron and nuclear physics on unstable nuclei, precision nuclear physics, strangeness nuclear physics, low-energy hadron physics, high-energy heavy-ion physics, nucleon structure, fundamental physics with nuclei, and computational nuclear physics. The updated version of this report was published in 2021 [2].

Within these reports in 2013 and 2021, S. Kumano contributed to the nucleon-structure section. We explained proton-spin puzzle, QCD factorization and parton distribution functions (PDFs), and lepton-proton and proton-proton scattering experiments and their global analyses for determining polarized PDFs. Transverse spin physics and higher-twist effects were also discussed. The proton-spin composition was shown in a color-gauge invariant way. For finding the origin of nucleon spin, the contribution from partonic orbital angular momenta should be determined by measuring three-dimensional structure functions. Furthermore, theoretical hadron models and lattice QCD results were summarized on the structure functions. Finally, we introduced future experimental projects, CERN-COMPASS, RHIC, Fermilab, KEKB, JLab, EIC, and J-PARC, on nucleon-structure physics.

19. Numerical solution of Q^2 evolution equations for fragmentation functions

Semi-inclusive hadron-production processes are becoming important in high-energy hadron reactions. They are used for investigating properties of quark-hadron matters in heavy-ion collisions, for finding the origin of nucleon spin in polarized lepton-nucleon and nucleon-

nucleon reactions, and possibly for finding exotic hadrons. For describing the hadron-production cross sections in high-energy reactions, fragmentation functions are essential quantities. A fragmentation function indicates the probability of producing a hadron from a parton in the leading order of the running coupling constant α_s. In 2013, the Belle and BaBar collaborations reported very precise experimental data on the fragmentation functions, which were much more accurate than the Large Electron-Positron Collider (LEP) and SLAC Large Detector (SLD). The LEP and SLD groups measured the fragmentation functions at the Z-mass region, whereas the Belle and BaBar measurements were at 10.5 GeV. It means that the scaling violation (Q^2 evolution) phenomena became clear for the first time by these data and it became possible to probe the gluon fragmentation functions.

The Q^2 dependence is described by the standard DGLAP (Dokshitzer-Gribov-Lipatov-Altarelli-Parisi) evolution equations, which are often used in theoretical and experimental analyses of the fragmentation functions and in calculating semi-inclusive cross sections. The DGLAP equations are complicated integro-differential equations, which cannot be solved in an analytical method. On the other hand, there was a strong need from scientists to use a Q^2 evolution code for their theoretical and experimental projects. The optimum fragmentation functions were supplied at fixed Q^2, usually small-Q^2 region where the perturbative QCD could be applied, so that they should be evolved to different Q^2 scales for their own experiments and theoretical model calculations. In our work, we explained a numerical solution method and created a Q^2 evolution code for general users. The DGLAP evolution equations are expressed by a differentiation of Q^2 and integrals of splitting functions multiplied by the fragmentation functions over the energy fraction z, which is defined by the ratio of the produced-hadron energy over the half of the center-of-mass energy.

In this work, a simple method was employed for solving the evolution equations by using the Euler method and the Gauss-Legendre quadrature for evaluating integrals, and a useful code was provided for calculating the Q^2 evolution of the fragmentation functions in the leading order (LO) and next-to-leading order (NLO) of α_s [24]. The renormalization scheme is $\overline{\text{MS}}$ in the NLO evolution. Our evolution code was explained for using it in one's studies on the fragmentation functions.

20. Test of CDF dijet anomaly within the standard model

In April of 2011, the Fermilab reported that the CDF (Collider Detector at Fermilab) collaboration discovered a new signature beyond the standard model by the proton-antiproton collision with the 1.96 TeV energy at Tevatron, and their work was published in Physical Review Letters 106 (2011) 171801. Observing produced W and 2 jets in the proton-antiproton collision, they found an unexplained peak in the cross section as the function of two-jet invariant mass. In order to confirm that this CDF result is a new discovery, we needed to show that such a peak cannot be reproduced with the standard model. In the W- and jet-production cross section, various parton distribution distributions (PDFs) are involved in the initial proton and antiproton, so that their accurate momentum distributions should be understood.

This dijet anomaly was investigated within the standard model by considering effects of the PDFs on various processes: W+dijet, Z+dijet, WW, ZW, and top production. Since the anomalous peak existed in the dijet-mass region of 140 GeV with the $p\bar{p}$ center-of-mass energy $\sqrt{s}$=1.96 TeV, a relevant momentum fraction x of partons is roughly 0.1. In this x region, recent HERMES semi-inclusive charged-lepton scattering experiment indicated that the strange-quark distribution could be very different from a conventional one $s \simeq 0.4(\bar{u}+\bar{d})/2$, which has been used for many years, based on opposite-sign dimuon measurements in neutrino-induced deep inelastic scattering. We investigated effects of such variations in the strange-quark distribution $s(x)$ on the anomaly [25]. We found that distributions of W+dijets and other process are affected by the strange-quark modifications in wide dijet-mass regions including the 140 GeV one. Since the CDF anomaly was observed in the shoulder region of the dijet-mass distribution, a slight modification of the distribution shape could explain at least partially the CDF excess. Therefore, it is important to consider such effects within the standard model for judging whether the CDF anomaly indicated new physics beyond the standard model. We also showed modification effects of the strange-quark distribution in the LHC (Large Hadron Collider) kinematics, where cross sections are sensitive to a smaller-x region of $s(x)$.

On the other hand, the strange-quark distribution itself contains interesting physics. We expect that the major part of $s(x)$ should be produced in perturbative-QCD process of the gluon splitting ($g \to s\bar{s}$). However, there could be a nonperturbative-QCD mechanism to produce $s(x)$ which is separate from the Q^2-evolution process, and it is called intrinsic strange. Because it has never been identified experimentally, it is an interesting topic by itself. Our paper was accepted in Physical Review D [25] two days after our submission, which indicated an importance and urgency of our work. Later, the anomalous peak disappeared by the CDF reanalysis. However, our theoretical studies are valid in any case and are independent from the existence of the original dijet anomaly.

21. Structure of $\Lambda_c(2940)^+$ by its strong and electromagnetic decays

A number of exotic hadrons were reported by the Belle and BaBar collaborations in heavy-quark hadron systems. One of them is $\Lambda_c(2940)^+$, which is considered as a molecular state of nucleon and D^*. However, there is a possibility of the D-wave excitation of $\Lambda_c(2286)^+$. In order to find its internal structure, we proposed to use its strong and electromagnetic decays. First, we studied the radiative decay $\Lambda_c(2940)^+ \to \Lambda_c(2286)^+\gamma$ by the hadron molecule picture and predicted its decay width [28]. We formulated the decay process by considering ND^* loops by paying attention to the proper gauge invariance. There was a large contribution in the radiation from the internal proton, and the other terms, radiations from D^*, Λ_c^+, and $\Lambda_c^+ND^*$ vertices, were relatively small. In the molecular scenario, the $\Lambda_c(2940)^+$ baryon was described by a superposition of $|pD^{*0}\rangle$ and $|nD^{*+}\rangle$ components with the explicit admixture expressed by the mixing angle θ ($|\Lambda_c(2940)^+\rangle = \cos\theta\,|pD^{*0}\rangle + \sin\theta\,|nD^{*+}\rangle$). The calculated radiative-decay widths displayed a sizable sensitivity to the mixing angle θ and to the scale parameter Λ. Especially, the cancellation between the contributions of the radiations from internal hadrons resulted in a rather pronounced θ-dependence. This effect could provide a stringent constraint on the role of the two molecular components pD^{*0} and nD^{*+} in the $\Lambda_c(2940)^+$ resonance. The decay width also depended much on the momentum cutoff parameter Λ at the $\Lambda_c^+ND^*$ vertex. We showed our decay width as the functions of θ and $\Lambda_c^+ND^*$. For example, it was 84 keV for $\theta = 10^\circ$ and $\Lambda = 1$ GeV. Possible future measurements of the radiative decay width could provide further insights into the structure of the $\Lambda_c(2940)^+$ state.

Second, we investigated the strong three-body decays $\Lambda_c(2940)^+ \to \Lambda_c(2286)^+\pi^+\pi^-$, $\Lambda_c(2286)^+\pi^0\pi^0$ by considering the same molecular composition [26]. In our calculation, we employed the extended SU(4) chiral Lagrangians to describe the interaction terms contained in $\mathcal{L}_{\pi D^* B B_h}$ and $\mathcal{L}_{\pi B B'}$. Therefore, the necessary couplings $g_{\pi D^* B B_h}$ and $g_{\pi B B'}$

were well determined. We showed the explicit contributions from the two-step processes $\Lambda_c(2940)^+ \to \Sigma_c^{++}\pi^- \to \Lambda_c(2286)^+ + \pi^+\pi^-$, $\Lambda_c(2940)^+ \to \Sigma_c^0\pi^+ \to \Lambda_c(2286)^+ + \pi^+\pi^-$, $\Lambda_c(2940)^+ \to \Sigma_c^+\pi^0 \to \Lambda_c(2286)^+ + \pi^0\pi^0$, and $\Lambda_c(2940)^+ \to \rho^0\Lambda_c(2286)^+ \to \Lambda_c(2286)^+ + \pi^+\pi^-$. In particular, the contribution $\Lambda_c(2940)^+ \to \Sigma_c\pi \to \Lambda_c(2286)^+ + \pi\pi$ was the largest, and the intermediate ρ term was essentially negligible. The charged decay mode involving $\pi^+\pi^-$ was less than two times larger than the neutral $\pi^0\pi^0$ mode. The strong decay widths were shown as the functions of the mixing angle θ and cutoff parameter Λ. For example, it was 4.9 MeV for $\theta = 10^\circ$ and $\Lambda = 1$ GeV. Our results for the three-body decay widths presented another test for the molecular interpretation of the $\Lambda_c(2940)^+$. We expect that future measurements of the radiative and strong decay widths will clarify the internal structure of $\Lambda_c(2940)^+$ in comparison with our theoretical predictions.

22. Clustering properties in nuclear structure functions

Many nuclei are described by the shell model, and their density distributions are shown by absolute value squared of wave functions. However, there are nuclei which cannot be easily described by the shell model with a limited number of model energy levels. These nuclei exist around the mass-number region of 10 and heavy unstable-nucleus region. They have cluster structure within nuclei. Recently, there were measurements on deep inelastic electron scattering measurements on a nucleus with the cluster structure, and we had much progress on structure functions and parton distribution functions for nuclei with clusters. An experimental group of the Thomas Jefferson National Accelerator Facility (JLab) measured the structure function F_2 for the beryllium-9 nucleus, and they showed the gradient of the nuclear modification with respect to the Bjorken-scaling variable x ($|d(F_2^A/F_2^D)/dx|$) as a function of average nuclear density. Although the slopes of the ^{3}He, ^{4}He, and ^{12}C nuclei were along the smooth line, the ^{9}Be slope was much different, which looked like an "anonymous" result.

In our studies, we pointed out that the phenomenon comes from the clustering effect in the ^{9}Be nucleus [27]. For understanding this anomalous nuclear effect for the beryllium-9 nucleus, clustering aspects were studied in the structure functions by using momentum distributions calculated in antisymmetrized or fermionic molecular dynamics (AMD or FMD) and also in a simple shell model for comparison. According to the AMD, the ^{9}Be nucleus consists of two α-like clusters with a surrounding neutron. The clustering produced high-momentum components in nuclear wave functions, which affected nuclear modifications of the structure functions. We investigated whether clustering features could appear in the structure function F_2 of ^{9}Be along with studies for other light nuclei. We found that nuclear modifications of F_2 are similar in both AMD and shell models within our simple convolution description although there are slight differences in ^{9}Be. It indicated that the anomalous ^{9}Be result should be explained by a different mechanism from the nuclear binding and Fermi motion. If nuclear-modification slopes $d(F_2^A/F_2^D)/dx$ are shown by the maximum local densities, the ^{9}Be anomaly can be explained by the AMD picture, namely by the clustering structure, whereas it certainly cannot be described in the simple shell model. This fact suggested that the large nuclear modification in ^{9}Be should be explained by large densities in the clusters. In our work, we considered that nuclear structure functions F_2^A consist of a mean conventional part and a remaining part depending on the maximum local density. The first mean part did not show a significant cluster effect on F_2. This is because of the average over the angle, although the local clusters exist in the nucleus. However, we proposed that the remaining part could explain the anonymous

JLab slope, and it is associated with high densities created by the cluster formation in ^{9}Be. The JLab measurement is possibly the first signature of clustering effects in high-energy nuclear reactions. A responsible physics could be an internal nucleon modification, which is caused by the high densities due to the cluster configuration, and/or a short-range correlation between nucleons. The clustering aspect of nuclear structure functions is an unexplored topic which is interesting for future investigations, and this project was proposed at JLab (JLab PAC-35 proposal, PR12-10-008).

23. Structure-function projections and optimum tensor-polarized PDFs for spin-1 deuteron

Spin structure of a spin-one hadron is interesting as a future research topic because there exist new tensor structure functions which do not appear in the spin-$\frac{1}{2}$ nucleon. There are eight structure functions, F_1, F_2, g_1, g_2, b_1, b_2, b_3, and b_4, in charged-lepton scattering from a spin-one hadron, whereas four of them (F_1, F_2, g_1, g_2) exist in the spin-1/2 nucleon. These additional structure functions vanish if internal constituents are in the S state, and they are related to tensor structure in spin-one hadrons. Studies of such tensor structure will open a new field of high-energy spin physics.

In our work, the projection operators were derived for the structure functions of a spin-one hadron by using combination of its momentum, polarization, and spin vectors [34]. They are useful in theoretical calculations because the structure functions need to be extracted from a calculated hadron tensor $W_{\mu\nu}$ in theoretical models, for example, the nuclear convolution model for the spin-1 deuteron.

Next, optimum tensor-polarized parton distribution functions (PDFs) were determined from HERMES experimental results on b_1 [29] for understanding the tensor structure in terms of quark and gluon degrees of freedom. Prior to this work, it was not clear how the HERMES measurements were related to the tensor-polarized PDFs. We determined optimum tensor-polarized PDFs for explaining the experimental data, so that theoretical-model calculations could be tested and also for submitting a new experimental proposal. The structure functions b_1 and b_2 are described by tensor-polarized quark and antiquark distributions $\delta_T q$ and $\delta_T \bar{q}$. Using HERMES data on the b_1 structure function for the deuteron, we made an analysis of extracting the distributions $\delta_T q$ and $\delta_T \bar{q}$ in a simple x-dependent functional form [29]. By imposing the sum rule $\int dx\, b_1(x) = 0$ suggested by the parton model, the optimum distributions were proposed for the tensor-polarized valence and antiquark distribution functions from the analysis of the HERMES data. A finite tensor polarization was obtained for antiquarks if we impose a constraint that the first moments of tensor-polarized valence-quark distributions vanish. It is interesting to investigate a physics mechanism to create a finite tensor-polarized antiquark distribution. The tensor-polarized PDFs were defined by unpolarized partons in a polarized hadron, so that their Q^2 scale evolution is given by the usual unpolarized DGLAP equations. However, the HERMES data are not accurate enough to probe the scale dependence and the data analysis was done by assuming no Q^2 evolution by fixing it at the HERMES-data average $Q^2 = 2.5$ GeV^2. We made the determined tensor-polarized PDFs available for general public. By this work, it became possible to investigate practically the deuteron tensor structure at high energies. In fact, the JLab experiment (Letter of Intent to JLab PAC-37) was submitted by using our tensor PDFs, and this experiment will be realized by the middle of 2020's.

24. Possible studies of GPDs and color transparency at hadron accelerator facilities

At the stage of 2008, only possibilities for measuring the generalized parton distributions (GPDs) were to use the virtual Compton scattering or hadron-production process at lepton accelerator facilities. We proposed that it is possible to investigate them at hadron accelerator facilities, such as J-PARC (Japan Proton Accelerator Research Complex) facility and GSI-FAIR (Gesellschaft für Schwerionenforschung -Facility for Antiproton and Ion Research) [31]. We considered a novel class of hard branching hadronic processes $a + b \to c + d + e$, where hadrons c and d have large and nearly opposite transverse momenta and large invariant energy which is a finite fraction of the total invariant energy, for investigating the GPDs. We showed that a number of GPDs can be investigated in hadron facilities such as J-PARC and GSI-FAIR. In this work, the GPDs for the nucleon and for the $N \to \Delta$ transition were studied in the reaction $N + N \to N + \pi + B$, where N, π, and B are a nucleon, a pion, and a baryon (nucleon or Δ), respectively, with a large momentum transfer between B (or π) and the incident nucleon. In particular, the Efremov-Radyushkin-Brodsky-Lepage (ERBL) region of the GPDs can be measured in such exclusive reactions. We estimated the cross section of the processes $N+N \to N+\pi+B$ by using current models for relevant GPDs and information about large angle πN reactions. We found that it is feasible to measure these cross sections at the high-energy hadron facilities, and to get novel information about the nucleon structure, for example, contributions of quark orbital angular momenta to the nucleon spin. The advantages of using the hadron reactions are that cross sections are generally larger than lepton reactions and that a specific kinematical region, so called the Efremov-Radyushkin-Brodsky-Lepage region $-\xi < x < \xi$ (x is the momentum fraction, ξ is the skewedness parameter), can be measured. If this experiment is realized, it will extend projects of the hadron accelerator facilities and the GPDs will be investigated from different viewpoint and kinematical regions.

Next, we proposed a possible study on color transparency by using a high-momentum pion beam [30]. It is valuable to investigate hadron interactions in nuclear medium for understanding fundamental hadron reactions and for applications to high-energy nuclear reactions. The cross section is dominated by a small hadron component in a reaction with large-momentum transfer. This small hadron passes through the hadron medium without much interactions, which is called color transparency (CT). The color transparency T is defined as the ratio of cross sections for nucleon-nucleus and nucleon-nucleon reactions [$T = \sigma_{NA}/(A\,\sigma_{NN})$]. As the hard scale of the reaction, for example the proton-beam energy, becomes larger, the transparency is expected to become larger. We demonstrated that hard branching $2 \to 3$ particle processes with nuclei provide an effective way to determine the momentum transfers needed for effects of point-like configurations to dominate large angle $2 \to 2$ processes, by showing the transparency as the functions of the pion-beam energy and nuclear mass. In contrast with previously proposed approaches, the discussed reaction allows the effects of the transverse size of configurations to be decoupled from effects of the space-time evolution of these configurations. It can be applied to a much broader range of two-body processes than the original method including meson-meson scattering ($\pi\pi, \pi K, KK$) where one expects an earlier onset of the CT regime than for meson (baryon)-baryon scattering. One could also look for the onset of CT in the meson-baryon ($\pi N, \Lambda\pi, ...$) and baryon-baryon ($pN, p\Delta, ...$) scattering. Studies with beams of energies in the 20-200 GeV range appear to be optimal for these purposes.

25. Determination of polarized PDFs with JLab and RHIC-Spin measurements

In order to understand the origin of the nucleon spin, we need to determine contributions from the quark and gluon spins by determining polarized parton distribution functions from experimental measurements. In this work, a global analysis was performed within the next-to-leading order in Quantum Chromodynamics (QCD) to determine polarized parton distributions with new experimental data in spin asymmetries [38]. The new data set included JLab, HERMES, and COMPASS measurements on spin asymmetry A_1 for the neutron and deuteron in lepton scattering. Our new analysis also utilized the double-spin asymmetry for π^0 production in polarized pp collisions, $A_{LL}^{\pi^0}$, measured by the PHENIX collaboration. The uncertainties of the polarized PDFs were estimated by the Hessian method. Because of these new data, uncertainties of the polarized PDFs were reduced. In particular, the JLab, HERMES, and COMPASS measurements were valuable for determining $\Delta d_v(x)$ at large x and $\Delta\bar{q}(x)$ at $x \sim 0.1$. The PHENIX π^0 data significantly reduced the uncertainty of $\Delta g(x)$. Furthermore, we discussed a possible constraint on $\Delta g(x)$ at large x by using the HERMES data on g_1^d in comparison with the COMPASS ones at $x \sim 0.05$.

We investigated impact of π^0-production data at Relativistic Heavy Ion Collider (RHIC) and future E07-011 experiment for the structure function g_1 of the deuteron at the Thomas Jefferson National Accelerator Facility (JLab) on studies of nucleonic spin structure, especially on the polarized gluon distribution function [32]. By global analyses of polarized lepton-nucleon scattering and the π^0-production data, polarized parton distribution functions were determined and their uncertainties were estimated by the Hessian method. Two types of the gluon distribution function were investigated. One was a positive distribution and the other was a node-type distribution which changes sign at $x \sim 0.1$. Although the RHIC π^0 data seemed to favor the node type for $\Delta g(x)$, it was difficult to determine a precise functional form from the current data. However, it was interesting to find that the gluon distribution $\Delta g(x)$ is positive at large x (> 0.2) due to constraints from the scaling violation in g_1 and RHIC π^0 data. The JLab-E07-011 measurements for g_1^d should be also able to reduce the gluon uncertainty, and the reduction was comparable to the one by RUN-5 π^0-production data at RHIC. The reduction was caused mainly by the error correlation between polarized antiquark and gluon distributions and by a next-to-leading-order (NLO) gluonic effect in the structure function g_1^d. We found that the JLab-E07-011 data are accurate enough to probe the NLO gluonic term in g_1. Both RHIC and JLab data contribute to better determination of the polarized gluon distribution in addition to improvement on polarized quark and antiquark distributions.

26. High-energy hadron physics at J-PARC

Nuclear structure and reactions are described by nucleons and other hadron degrees of freedom, and this field became one of established ones. The underlying fundamental theory of strong interaction is QCD. However, it cannot be solved in nonperturbative regions especially at finite densities, and it is sometimes difficult to understand hadronic and nuclear structure and reactions as many-body systems in terms of quarks and gluons. In this situation, the J-PARC has projects to create new particles and quark-hadron matters by changing the flavor and hadron density. It is the most-intense hadron-beam facility in the multi-GeV high-energy region. By using secondary beams of kaons, pions, and others as well as the primary-beam proton, the facility could cover a wide range of hadron physics from strongly interacting many-body systems with an extended hadronic degree of freedom, strangeness, to new forms of hadrons and hadronic matters. At the first stage of the J-PARC operation, hadron topics are mainly on strangeness nuclear physics such as hypernuclei and kaonic nuclei. Then, the studies could be extended to exotic hadron searches, chiral dynamics in nuclear medium, structure functions, and hard exclusive processes. With major upgrades of the facility, extensive studies could be done for the nucleon spin and heavy-ion physics. In particular, new projects became possible by using the newly-constructed high-momentum beamline from 2020.

In Ref. [33], possible J-PARC projects were explained in high-energy hadron physics, particularly by using the 30−50 GeV primary proton beam. Such proton reactions are in a limit region where the perturbative QCD can be applied, so that such projects have fundamental importance in understanding QCD physics from a perturbative region to a nonperturbative one. There are proposed experiments on charm-production and Drell-Yan processes as well as single spin asymmetries for investigating quark and gluon structure of the nucleons and nuclei. Parton-energy loss could be studied in the Drell-Yan processes. There is also a proposal on hadron-mass modifications in a nuclear medium by using the proton beam. These topics include flavor dependence of antiquark distributions, transverse-momentum-dependent distributions such as the Boer-Mulders and Sivers functions, and polarized exclusive reactions. In addition, possible topics are transition from hadron to quark degrees of freedom by elastic pp scattering, color transparency by $(p, 2p)$, short-range correlation in nuclear force by $(p, 2pN)$, tensor structure functions for spin-1 hadrons, fragmentation functions, and generalized parton distributions although proposals are not written on these projects. If proton-beam polarization will be attained, it is possible to investigate details of nucleon spin structure. The J-PARC is an excellent accelerator facility to investigate diverse hadron projects, and we expand the projects to various fields in future [S. Kumano, Nucl. Phys. A782 (2007) 442; AIP Conf. Proc. 1056 (2008) 444; J. Phys. Conf. Ser. 312 (2011) 032005].

27. Determination of nuclear parton distribution functions in the next-to-leading order

High-energy heavy-ion reactions have been investigated at RHIC and LHC for finding properties of quark-gluon plasma from their cross sections. For describing the cross sections, accurate nuclear parton distribution functions (NPDFs) are needed. In addition, for neutrino oscillation measurements, they also need accurate PDFs for the oxygen nucleus because systematic errors are dominated by the neutrino-nucleus interaction part. There exist 10−20% nuclear modifications for medium nuclei. It is important to understand modification mechanisms not only for finding physics of nuclear PDFs but also for applications to the high-energy nuclear reactions. For example, neutrino experimentalists ask us to calculate neutrino cross sections within 5% accuracy for future oscillation experiments intended to measure the CP violation in the lepton sector.

The NPDFs were determined by global analyses of experimental data on structure-function ratios $F_2^A/F_2^{A'}$ and Drell-Yan cross-section ratios $\sigma_{DY}^A/\sigma_{DY}^{A'}$ [36]. The analyses were done in the leading order (LO) and next-to-leading order (NLO) of running coupling constant α_s. It was successful in explaining the data from the deuteron to a large lead nucleus. The uncertainties of the determined NPDFs were estimated by the Hessian method in both LO and NLO, so that we can discuss the NLO improvement on the determination. We found slight NLO improvements for the antiquark and gluon distributions at small x $(= 0.01 - 0.001)$; however, they were not significant at larger x. Valence-quark distributions were well determined, and antiquark distributions were also determined at $x < 0.1$. However, the antiquark distributions had large uncertainties at $x > 0.2$. The gluon modifications could not be fixed. The valence-quark distributions were determined well from the F_2^A/F_2^D measurements at $x > 0.3$, and they were constrained at small x by the baryon-number conservation and charge conservation. The antiquark distributions were determined from the F_2 data at $x < 0.05$ and there was almost no nuclear modification at $x = 0.1$ due to the Drell-Yan data σ_{pA}/σ_{pD}, and they had large errors in the larger-x region. Although the advantage of the NLO analysis, in comparison with the LO one, is generally the sensitivity to the gluon distributions, gluon uncertainties were almost the same in the LO and NLO. It was because scaling-violation data are not accurate enough to determine precise nuclear gluon distributions. Modifications of the PDFs in the deuteron were also discussed by including data on the proton-deuteron ratio F_2^D/F_2^p in the analysis. A code was provided for calculating the NPDFs and their uncertainties at given x and Q^2 in the LO and NLO.

28. HERMES effect

From charged-lepton deep inelastic scattering measurements, two nuclear structure functions F_1^A and F_2^A are measured. By virtual-photon polarizations, F_1^A is associated with the transverse polarization and F_2^A is with both transverse and longitudinal polarizations. Removing the transverse part from F_2^A, we obtain the longitudinal structure function F_L^A. Although it should vanish ($F_L^A = 0$) in the scaling limit $Q^2 \to \infty$, the longitudinal-transverse structure function ratio $R = F_L^A/F_1^A$ is finite in Q^2 regions of actual experiments. In the 1980's, nuclear modifications on F_2^A were studied extensively, and they are known as the EMC (European Muon Collaboration) effect. Therefore, scientists started thinking about a possible nuclear modification in the ratio R in the 1990's. In 2000, the HERMES collaboration reported the existence of a nuclear modification in the longitudinal-transverse structure function ratio R, so that it used to be called a HERMES effect.

We claimed that such a nuclear effect should exist in the medium and large x regions [43]. Using a convolution description of nuclear structure functions, we derived the nuclear modification of the longitudinal-transverse structure function ratio $R(x, Q^2)$ at medium and large x. We found that the conventional convolution description of the nuclear structure functions leads to the nuclear modification of the transverse-longitudinal structure function ratio $R(x, Q^2)$. The physical origin of the modification is the transverse-longitudinal admixture of the nuclear structure functions due to the nucleon momentum transverse to the virtual photon momentum. Namely, the longitudinal structure function F_L^A of a nucleus is described by both nucleonic structure functions F_L^N and F_1^N convoluted with nucleon momentum distributions in the nucleus. For example, electron-nucleon scattering cross sections and structure functions are described by taking the virtual-photon-momentum direction as the z axis and the nucleon is at rest or moves in the $-z$ direction. However, nucleons in a nucleus move in any spacial directions due to Fermi motion, so that the transverse and longitudinal structure functions mix. The mixing effects we found were moderate at small Q^2 and disappear at large Q^2. The nuclear modification effects are dominated by the binding and Fermi-motion effects contained implicitly in the convolution expression. Since the mixture occurs by the Fermi motion, such effects appear especially at large x. Although a later HERMES reanalysis seemed to deny the originally reported modification at small x, our theoretical results are valid and independent from the original HERMES finding at small x. We hope that such nuclear effects will be found experimentally in future.

29. Nuclear effects and possible explanations on the NuTeV weak-mixing $\sin^2\theta_W$ anomaly

    Neutral currents contain not only isospin currents, which act on left-hand components, but also electromagnetic currents which act on both left- and right-handed ones. The mixing fraction of these currents is called the weak-mixing angle or Weinberg angle θ_W. This angle was accurately measured by collider experiments as $\sin^2\theta_W = 0.2227 \pm 0.0004$ at the stage of 2002. However, the NuTeV collaboration reported anomalously large weak mixing angle in comparison with the standard-model prediction. The NuTeV result, $\sin^2\theta_W = 0.2277 \pm 0.0013\,(\text{stat}) \pm 0.0009\,(\text{syst})$, was significantly different from a global analysis of other data, $\sin^2\theta_W = 0.2227 \pm 0.0004$. This is called the NuTeV weak-mixing-angle anomaly. Since the mixing angle $\sin^2\theta_W$ is one of important physics quantities, it is important to find a reason for the difference. Neutrino and antineutrino charged- and neutral-current events were analyzed for extracting $\sin^2\theta_W$ in the NuTeV experiment. The Paschos-Wolfenstein relation $R^- = (\sigma^{\nu N}_{NC} - \sigma^{\bar{\nu} N}_{NC})/(\sigma^{\nu N}_{CC} - \sigma^{\bar{\nu} N}_{CC}) = 1/2 - \sin^2\theta_W$ was used for its determination, and this relation was derived for the isoscalar nucleon.

    Since the NuTeV target was the iron instead of the isoscalar nucleon, various correction factors needed to be considered to this Paschos-Wolfenstein relation. In addition, this relation was obtained by assuming the isospin symmetry in the parton distribution functions (PDFs) of the neutron to relate them to the PDFs of the proton. We showed the correction terms to the Paschos-Wolfenstein relation from isospin breaking in the PDFs, nuclear correction difference between u_v and d_v, finite distributions of $s(x) - \bar{s}(x)$ and $c(x) - \bar{c}(x)$, and neutron-excess effects, and we indicated that the NuTeV anomaly could originate from these corrections [44]. Next, using charge and baryon-number conservations for nuclei, we discussed an effect of nuclear modification difference between u_v and d_v on the $\sin^2\theta_W$ through the modified Paschos-Wolfenstein relation [39]. These modifications had been assumed to be identical, but it could be different. According to the analysis, the effect could partially explain the NuTeV anomaly; however, such a difference cannot be determined from the current experimental measurements. We need further studies about the nuclear effect on the NuTeV deviation. Even at the stage of 2020, uncertainties are very large for the nuclear modification difference between u_v and d_v, isospin violation effects on the PDFs, $s(x) - \bar{s}(x)$, and $c(x) - \bar{c}(x)$, so that the origin of the NuTeV anomaly is not solved undoubtedly.

30. Studies of nucleonic and nuclear structure functions at neutrino factories

    Neutrino interactions are weak, so that their cross sections are generally small and measurement errors are large. For future developments of precise neutrino physics, a high-intensity neutrino factory is necessary and we contributed to this project. We investigated possible hadron-structure studies at the high-energy neutrino factory by using our experiences on nucleon structure functions [S. Kumano, Nucl. Phys. Proc. Suppl. 112 (2002) 42; AIP Conf. Proc. 721 (2004) 29]. In particular, possible studies were discussed in connection with recent studies of the PDFs (parton distribution functions) in the nucleons and nuclei.

    In neutrino-nucleon deep inelastic scattering, there exists a new structure function F_3, which does not exist in the charged-lepton scattering, due to the additional axial vector current. Since this structure function is expressed by valence-quark distributions in the nucleon, neutrino scattering data played an important role in determining them. The nuclear modifications of the valence-quark distributions are found at medium and large x from the modification of F_2 in charged-lepton scattering; however, it is not easy to find them at small x although there are some constraints due to baryon-number and charge conservations. The neutrino reactions should be valuable for finding nuclear modification of valence-quark distributions at small x if structure function ratios F_3^A/F_3^D are measured for various nuclei. Nuclear shadowing mechanism should be tested by finding such valence modifications.

Next, possible studies of polarized PDFs at the neutrino factory were discussed. In charged-lepton scattering, it is difficult to separate the contribution of valence quarks from the antiquark one; however, it could be done in neutrino scattering. There are new polarized structure functions g_3, g_4, and g_5 in neutrino reactions. Using these functions as well as g_1 and g_2, we should be able to establish the nucleon spin structure. The polarized valence-quark distributions should be determined by the structure function g_3 (or g_5 notation in some researchers). Furthermore, the quark spin content is directly obtained by measuring the structure function g_1, whereas analysis of charged-lepton data have uncertainties.

31. Flavor asymmetry in polarized antiquark distributions

Antiquark distributions of the nucleon are produced mainly through the perturbative splitting process $g \to q\bar{q}$. Then, up- and down-quark masses are small, so that the $\bar{u}$ and $\bar{d}$ antiquark distributions are considered to be the same. However, it is known that there exists flavor dependence in the unpolarized light-antiquark distributions. It was not obvious whether there is flavor dependence in polarized light-antiquark distributions. For understanding the origin of nucleon spin and nucleon structure in general including spin, we needed to know the non-perturbative mechanisms to create the flavor dependence.

The flavor asymmetry was investigated in the polarized light-antiquark distributions by a meson-cloud model [45], which was used for explaining the flavor-asymmetry phenomena in unpolarized antiquark distributions. The existence of "meson clouds" is known, for example, from the negative experimental mean-square radius ($\langle r^2 \rangle < 0$) of the neutron. Since the pion is a scalar particle, it does not contribute directly to the polarized asymmetry $\Delta\bar{u} - \Delta\bar{d}$. We calculated spin-1 ρ meson contributions to $\Delta\bar{u} - \Delta\bar{d}$ by considering that the virtual photon from a charged lepton interacts with the ρ meson. We pointed out that the g_2 part of ρ contributes to the structure function g_1 of the proton in addition to the ordinary longitudinally polarized distributions in ρ. This kind of contribution became important at medium x (> 0.2) with small Q^2 ($\sim$1 GeV^2). Including $N \to \rho N$ and $N \to \rho\Delta$ splitting processes, we obtained the polarized-ρ effects on the light-antiquark flavor asymmetry in the proton. The results showed $\Delta\bar{d}$ excess over $\Delta\bar{u}$, which is very different from some theoretical predictions. Our model could be tested by future experiments by RHIC-Spin and COMPASS collaborations.

Furthermore, we studied the relation between the ratio of the proton-deuteron (pd) Drell-Yan cross section to the proton-proton (pp) one $\Delta_{(T)}\sigma_{pd}/2\Delta_{(T)}\sigma_{pp}$ and the flavor asymmetry in polarized light-antiquark distributions [48]. Using our formalism of the polarized *pd* Drell-Yan process, we showed that the difference between the *pp* and *pd* cross sections is valuable for finding not only the flavor asymmetry in longitudinally polarized antiquark distributions but also the one in transversity distributions. It is especially important that we pointed out the possibility of measuring the flavor asymmetry in the transversity distributions because it cannot be found in W production processes and inclusive lepton scattering due to the chiral-odd property.

32. Determination of parton distribution functions in nuclei

In order to describe high-energy nuclear reactions, we need to have accurate nuclear parton distribution functions (PDFs). They have important applications for understanding properties of quark-gluon plasma and nuclear corrections to neutrino oscillation experiments. However, there were not serious studies on determination of the nuclear PDFs such as the CTEQ, GRV, and MRST analyses of the nucleonic PDFs.

We determined the optimum nuclear PDFs for the first time by using a χ^2 analysis method [46]. Since it was the first attempt, the analysis method was developed including the initial functional form of the Bjorken variable x. Nuclear modifications are about 10−20% for medium-size nuclei, so that we decided to determine such modifications from the nucleonic PDFs, which were relatively-well determined from other analyses, instead of the nuclear PDFs directly. The nuclear modifications depend on the variable x. There are negative shadowing corrections at small x, positive antishadowing ones at $x \simeq 0.1$, negative nuclear-binding ones, and positive nucleon Fermi-motion ones at $x > 0.7$. To approximate these x-dependent effects, quadratic or cubic functions of x with the factor $1/(1-x)$ are used in the analysis. About the mass number (A) dependence, we had the following consideration. Nuclear reaction cross sections are generally described by the volume term proportional to A and the surface one with the factor $A^{2/3}$ ($\sigma_A = A\sigma_V + A^{2/3}\sigma_S$). Then, the cross section per nucleon is expressed as $\sigma_A/A = \sigma_V + \sigma_S/A^{1/3}$, so that the $1/A^{1/3}$ dependence is expected in the nuclear PDFs.

Using these x- and A-dependent functionals, we determined the nuclear PDFs in the leading order of α_s by a χ^2 analysis. The parton distributions were provided at Q^2=1 GeV^2 with a number of parameters, which were determined by a χ^2 analysis of the data on nuclear structure functions. Although valence-quark distributions in the medium-x region were relatively well determined, the small-x distributions depended slightly on the assumed functional form. It was difficult to determine the antiquark distributions at medium x and gluon distributions in the whole-x region. From the analysis, we proposed the parton distributions at Q^2=1 GeV^2 for nuclei from deuteron to heavy ones with the mass number $A \sim 208$. They were provided either analytical expressions or computer subroutines for practical usage. Our studies should be important for understanding the physics mechanism of the nuclear modification and also for applications to heavy-ion reactions. This kind of nuclear parametrization should also affect existing parametrization studies in the nucleon because "nuclear" data are partially used for obtaining the optimum distributions in the "nucleon".

33. Polarized proton-deuteron Drell-Yan processes and polarized parton distributions

Formalisms of high-energy polarized proton-proton reactions were investigated in details and they are basics of performing RHIC-Spin experiments. High-energy hadron reactions with spin-1 hadrons had never been investigated in connection with polarized structure functions specific to spin-1 nature. In 1990's, polarized deuteron acceleration was studied among BNL accelerator scientists as a next project of the RHIC spin; however, nobody knew what kind of new spin observables are possible. In this situation, we proposed a general formalism for the structure functions which can be investigated in the polarized Drell-Yan processes with spin-1/2 and spin-1 hadrons [48,49,50], namely in the polarized proton-deuteron Drell-Yan processes.

Because of the spin-1 nature, there are new structure functions which cannot be studied in the proton-proton reactions. Imposing Hermiticity, parity conservation, and time-reversal invariance, we found that 108 structure functions exist in the Drell-Yan processes [50]. However, the number reduced to 22 after integrating the cross section over the virtual-photon transverse momentum $\vec{Q}_T$ or after taking the limit $Q_T \to 0$. There are 11 new structure functions in addition to the 11 ones in the Drell-Yan processes of spin-1/2 hadrons. The additional structure functions are associated with the tensor structure of the spin-1 hadron, and they could be measured by quadrupole spin asymmetries.

Then, we analyzed the polarized Drell-Yan processes with spin-1/2 and spin-1 hadrons in a parton model [49]. Quark and antiquark correlation functions were expressed in terms of possible combinations of Lorentz vectors and pseudovectors with the constrains of Hermiticity, parity conservation, and time-reversal invariance. Then, the analysis indicated that there are only four structure functions in the $\vec{Q}_T$-integrated case. They are unpolarized, longitudinally-polarized, transversity, tensor-polarized structure functions. The tensor-structure functions were related to the tensor polarized distribution b_1, and it does not exist in the proton-proton reactions. The Drell-Yan processes have an advantage over the lepton reaction in the sense that the antiquark tensor polarizations could be extracted easily [48].

The deuteron acceleration was not realized in the RHIC-Spin project; however, such a project could provide a new opportunity in a next generation high-energy spin physics. In fact, the proton-deuteron Drell-Yan experiment is under consideration in the Fermilab-E1039 project with a fixed polarized-deuteron target at the stage of 2020. Furthermore, our formalism can be used at other accelerator facilities such as GSI-FAIR, NICA, and possibly EIC if a fixed-target experiment is possible. The b_1 experiment will start at JLab by the middle of 2020's, and the proton-deuteron reactions are complementary to this JLab experiment in the sense that it probes a different kinematical region of x and Q^2 and that it could be used for determining the vector- and tensor-polarized antiquark distributions.

34. Determination of polarized parton distribution functions

There were relatively-established unpolarized parton distribution functions (PDFs) for the nucleon at the stage of 2000, as they had been investigated extensively by a few theory groups such as the CTEQ (Coordinated Theoretical-Experimental Project on QCD). However, studies of polarized PDFs were at a premature stage, so that we attempted to determine optimum longitudinally-polarized PDFs by an analysis of world data on polarized charged-lepton scattering from the polarized nucleon [42,47].

Since the measurement of the polarized structure function g_1 for the nucleon by the EMC, the origin of the nucleon spin has been investigated. However, it was not clear how antiquark and gluon spins contributed to the nucleon spin. We determined the polarized parton distribution functions by using the data from the longitudinally-polarized deep inelastic scattering experiments [47]. The studies were done by creating a Japanese collaboration, which is called Asymmetry Analysis Collaboration (AAC), among theoretical and experimental researchers in high-energy spin physics. It was intended to propose the optimum polarized PDFs by the analysis of g_1 data of the proton, deuteron, and ^{3}He. A new parametrization of the polarized PDFs was adopted by taking into account the positivity and the counting rule. The polarized PDFs were given at $Q^2 = 1$ GeV^2 by parameters, and then spin asymmetry A_1 was calculated theoretically. From the fit to the asymmetry data A_1, the polarized distribution functions of u- and d-valence quarks, sea quarks, and gluon were obtained. The results indicated that the quark spin content was $\Delta\Sigma$ =0.20 and 0.05 in the leading order (LO) and the next-to-leading-order (NLO) $\overline{\text{MS}}$

scheme, respectively. However, if x dependence of the sea-quark distribution was fixed at small x by "perturbative QCD" and Regge theory, it became $\Delta\Sigma = 0.24 \sim 0.28$ in the NLO. The small-x behavior could not be uniquely determined by the existing data, which indicated the importance of future experiments. From our analysis, we proposed one set of LO distributions and two sets of NLO ones as the longitudinally-polarized parton distribution functions. The gluon-spin contribution was positive and the antiquark one was a small negative value.

Then, errors of the determined polarized PDFs were estimated by the Hessian method [42]. In the χ^2 analysis, an error matrix was obtained and it was used for calculating error bands of the polarized PDFs. As a result, the polarized valence-quark distributions were relatively well determined, the polarized gluon distribution had a large error. Therefore, even $\Delta g = 0$ could be possible by considering the error. In this way, the gluon polarization could not be fixed by the charged-lepton DIS data, so that we may reply on RHIC measurements. We made an AAC code for calculating the determined polarized PDFs, and it has been used as one of standard parametrization models for the polarized PDFs.

35. Anomalous dimensions of the structure function h_1 and its Q^2 evolution

The nucleon spin structure was investigated mainly for longitudinal polarizations; however, transverse spin structure also needed to be understood. One of important transverse structure functions is the structure function h_1, which is also called the quark transversity distribution, and it is a leading-twist (twist 2) function. The quark transversity distribution is associated with the quark spin-flip amplitude, so that it is a chiral-odd distribution. Although there were experimental plans to measure it, the Q^2 evolution of h_1 was known only in the leading order (LO) of α_s at the time of 1996.

Since the scaling violation is usually calculated by including, at least, next-to-leading-order (NLO) terms, we studied two-loop anomalous dimensions for h_1 in the minimal subtraction (MS) scheme [54]. In order to study h_1 in perturbative Quantum Chromodynamics (QCD), we needed to introduce a set of local operators $O^{\nu\mu_1\cdots\mu_n} = S_n \overline{\psi}\, i\, \gamma_5\, \sigma^{\nu\mu_1}\, iD^{\mu_2} \cdots iD^{\mu_n}\, \psi -$ trace terms $(n = 1, 2, ...)$. The bare operator is defined by $O_B^n = Z_{O^n} O_R^n$ with the renormalized one O_R^n. Anomalous dimensions for O^n are given by these renormalization constants as $\gamma_{O^n} = \mu\, \partial(\ln Z_{O^n})/\partial\mu$. Dimensional regularization and Feynman gauge were used for calculating the two-loop contributions. In dimensional regularization with the dimension $d = 4 - \epsilon$, we tried to find $1/\epsilon$ singularities in the renormalization constants for calculating the anomalous dimensions. Due to the chiral-odd nature, the gluon transversity does not exist in the nucleon, as mentioned in the topic item 6. We calculated all the Feynman diagrams in the two-loop level by using the Feynman gauge and the MS scheme for obtaining the anomalous dimensions for h_1. Because of our studies, it became possible to investigate h_1 in the NLO level.

Next, by calculating the inverse Mellin transformation of the obtained anomalous dimensions, the Q^2 evolution can be described by integrodifferential equations in the DGLAP (Dokshitzer-Gribov-Lipatov-Altarelli-Parisi) form. We investigated numerical solution of the DGLAP Q^2 evolution equation for the transversity distribution $\Delta_T q$ or the structure function h_1 [51]. The LO and NLO evolution equations were studied. The renormalization scheme was MS or $\overline{\text{MS}}$ in the NLO case. Dividing the variables x and Q^2 into small steps, we solved the integrodifferential equation by the Euler method in the variable Q^2 and by the Simpson method in the variable x. We provided a FORTRAN program for the Q^2 evolution and devolution of the transversity distribution $\Delta_T q$ or h_1. Using the program, we showed the LO and NLO evolution results of the valence-quark distribution $\Delta_T u_v + \Delta_T d_v$, the singlet distribution $\sum_i(\Delta_T q_i + \Delta_T \bar{q}_i)$, and the flavor-asymmetric distribution $\Delta_T \bar{u} - \Delta_T \bar{d}$. They were compared with the longitudinal evolution results [52] to show unique features of the transversity evolution by finding differences. For example, Q^2 variations were much smaller in the flavor-nonsinglet transversity distribution than the one for the longitudinally-polarized distribution as the Q^2 is increased. In addition, perturbative effects on the flavor asymmetric distribution $\Delta_T \bar{u} - \Delta_T \bar{d}$ were conspicuous in the large-x region, in comparison with the ones for the longitudinally-polarized one, by using the developed codes. Using these results, we predicted various spin asymmetries possibly in the RHIC-Spin project.

36. Nuclear structure functions F_2^A by a parton model

Nuclear modifications of the structure function F_2 are known as the EMC (European Muon Collaboration) effect, and various mechanisms contribute to them depending on the Bjorken scaling variable x. We investigated a parton model which describes the nuclear structure functions F_2^A and nuclear parton distribution functions as an unified description from small x to large x [60,61,62]. As this parton model, we used a Q^2 rescaling model with parton-recombination effects. The average separation of nucleons in a nucleus is about 2.2 fm, which is almost equal to the nucleon diameter. This fact indicates that a quark confinement radius could change due to possible fusions of two nucleons in a nucleus, and it could result in the scale change, Q^2 rescaling in this work, within F_2^A. In addition, the confinement radius of a parton becomes larger than the average nucleon separation at small x, so that partons in different nucleons could interact with each other. This phenomena is called parton recombinations. We used a parton model which has these two mechanisms for describing the nuclear structure functions.

First, we calculated nuclear structure functions $F_2(x)$ from small $x\,(= 10^{-3})$ to large $x\,(= 0.9)$ in this parton model in order to compare them with experimental data of SLAC, EMC, NMC (New Muon Collaboration), and Fermilab-E665 [60,61]. As a result, we obtained a reasonably good agreement with the experimental data in the region $(0.005 < x < 0.8)$. In the large x region, the ratio $F_2^A(x)/F_2^D(x)$ (> 1) was explained by quark-gluon recombinations, which produced results similar to those by the nucleon Fermi motion. In the medium x region, the EMC effect was mainly due to the Q^2 rescaling mechanism in our model. In the small x region, shadowing effects were obtained through modifications in gluon distributions. However, our shadowing effects at very small $x\,(< 0.01)$ were very sensitive to the input gluon distribution of the nucleon.

Then, we investigated gluon distributions in the nuclei C and Sn by this parton model [62]. We obtained shadowing in the nuclear gluon distributions in the small x region $(x < 0.02)$ due to the recombinations and depletion [typically $G_A(x)/G_N(x) \sim 0.9$] in the medium x region $(0.2 < x < 0.6)$. The ratio $G_A(x)/G_N(x)$ became large at $x > 0.6$ due to gluon fusions from different nucleons. The ratio in the medium-large x region was very sensitive to the momentum cutoff for leak-out partons in our model. Comparisons with the NMC data on $G_{Sn}(x)/G_C(x)$ indicated that more accurate experimental data are needed for the nuclear gluon distributions. By our studies, the general features of nuclear structure functions were understood in the wide x region from small x (~ 0.001) to large x (~ 0.9) by the parton model with the rescaling and recombination effects.

37. Parton distributions in nuclei by a parton model

Using the parton model explained in the previous topic item 36, we predicted new phenomena in nuclear parton distribution functions. First, we showed that finite flavor-asymmetric antiquark distributions are possible [59], even if the antiquark distributions were flavor symmetric ($\bar{u} - \bar{d} = 0$) in the nucleon, due to the parton recombinations. In order to test the NMC finding of flavor asymmetry $\overline{u} - \overline{d}$ in the nucleon, existing Drell-Yan data for the tungsten target were often used. However, we have to be careful in comparing nuclear data with the nucleon ones. We investigated whether there exists a significant nuclear modification of the $\overline{u} - \overline{d}$ distribution in the parton-recombination model. In neutron-excess nuclei such as the tungsten, there exist more d-valence quarks than u-valence quarks, so that more $\overline{d}$ quarks are lost than $\overline{u}$ quarks due to parton recombinations [59]. Our results suggested that the nuclear modification in the tungsten is a 2–10 % effect on the NMC $\overline{u} - \overline{d}$ distribution. In the beginning of 2020's, Drell-Yan measurements will be reported from the Fermilab experiments with various nuclear targets, so that the nuclear $\bar{u} - \bar{d}$ will become a popular topic for finding its generation mechanism in the near future.

Second, nuclear modifications of structure function F_3^A and valence-quark distributions were investigated [57], particularly focusing on the small-x region to shed light on different shadowing mechanisms. Namely, this work was intended to distinguish between two typical shadowing models, the parton-recombination model and the vector-meson-dominance (VMD) model. We found that the nuclear modifications of the valence-quark distributions tend to increase at small x in the recombination model, and it was opposite to the one by the VMD model. Namely, we found that these models predict completely different behavior at small x. Therefore, studies of the ratio F_3^A/F_3^D at small x could be useful in discriminating among different models, which produce similar shadowing behavior in the structure function F_2. This difference could be tested experimentally by neutrino scattering measurements and also by π productions in charged-lepton scattering.

Third, Q^2 evolution of nuclear structure functions was investigated in order to understand NMC measurements on the tin and carbon nucleus ratio of F_2^A [55]. The F_2 was evolved by using the leading-order DGLAP, next-to-leading-order DGLAP, and parton-recombination equations. The NMC experimental result $\partial[F_2^{Sn}/F_2^C]/\partial[\ln Q^2] \neq 0$ could be essentially understood by the difference of parton distributions in the tin and carbon nuclei. However, there were some discrepancies from the data if the Q^2 evolution with the parton recombinations was used. It indicated that high-twist effects need to be understood accurately.

Forth, we investigated effects on J/ψ suppression in heavy-ion collisions. Originally, the J/ψ suppression was discussed by assuming that nuclear modifications are identical for both quark and gluon distributions. However, if both modifications are different in central and peripheral regions of nuclei or nuclear collisions, they should be properly taken into account. We estimated that such effects, namely the difference of the gluonic EMC effect from the quark one, can contribute to the J/ψ suppression about $5-10\%$.

38. Scalar meson substructure at ϕ factories

According to the basic quark model by Gell-Mann and Zweig, mesons and baryons consist of quark compositions $q\bar{q}$ and qqq, respectively, and hadrons with other quark configurations are called exotic hadrons. Scalar mesons below 1 GeV had been a persistent problem in hadron spectroscopy until recently. The scalar mesons, $f_0(980)$ and $a_0(980)$, are considered as exotic hadron candidates, for example, because strong decay widths are too large to explain experimental ones if they are ordinary $q\bar{q}$ hadrons with light u and d quarks. They were considered as $s\bar{s}$, $K\bar{K}$ molecule, tetraquark ($qq\bar{q}\bar{q}$), or glueball (gg). At the stage of 1993 when this work was done, there were future experimental facility possibilities of ϕ factory at Frascati and KEK.

In order to determine their structure, we proposed to use the radiative decay of ϕ meson into these scalar mesons at ϕ factories by calculating the decay widths in different configurations (ordinary $q\bar{q}$ mesons, $s\bar{s}$, $K\bar{K}$ molecule, tetraquark, or glueball) [63]. The radiative decay $\phi \to S\gamma$ [$S = f_0(980)$ or $a_0(980)$] is the electric dipole decay. Since the electric dipole moment is proportional to the spatial separation, the decay widths are sensitive to the internal structure of the scalar mesons. We showed that ϕ radiative decays into scalar mesons [$f_0(980)$, $a_0(980)$] could provide important clues on the internal structures of these mesons. The radiative decay widths varied widely depending on the substructures ($q\bar{q}$, $qq\bar{q}\bar{q}$, $K\bar{K}$, glueball). Hence, we could discriminate among various models by measuring these widths at the ϕ factories. The understanding of these meson structures is valuable not only in hadron spectroscopy but also in nuclear physics in connection with the widely-used but little-understood σ meson. Actually, our calculations indicated that the decay width is large [BR(4×10^{-5})] if S is a loose $K\bar{K}$ bound state, because the average $K\bar{K}$ separation is large. If S were a glueball, although such a possibility is denied at the stage of 2020 by lattice QCD, the decay width was smaller [BR($10^{-5} - 10^{-6}$)]. In this way, we showed that the internal structure of the scalar mesons $f_0(980)$ and $a_0(980)$ could be investigated at the ϕ factories. We also found that the decay $\phi \to S\gamma \to K^0\bar{K}^0\gamma$ is not strong enough to pose a significant background problem for studying CP violation via $\phi \to K^0\bar{K}^0$ at the ϕ factories. Later, the radiative decay widths were measured, and they, together with other experimental measurements, indicated that the scalar mesons are tetraquark hadrons or $K\bar{K}$ molecules.

39. Numerical solution of Q^2 evolution equations on structure functions

The DGLAP (Dokshitzer-Gribov-Lipatov-Altarelli-Parisi) evolution equations are integrodifferential equations, which describe Q^2 variations of structure functions. They cannot be easily solved, especially if complicated higher-order perturbative QCD corrections are included in splitting functions. However, they are important in practical applications such as in theoretical model calculations of the structure functions and comparisons with and analysis of experimental measurements. We investigated numerical solutions of the DGLAP evolution equations by using the Laguerre-polynomial method [58,64] and by the Euler's (or "Brute-force") method [51,52,56].

First, this Laguerre-polynomial method was studied by expanding parton distribution functions and the splitting functions in terms of the orthogonal Laguerre polynomials. The Laguerre method is considered to be a very efficient method for solving the DGLAP equations, and we extended this method for spin-dependent problems. As a result, accurate numerical solutions were obtained in the region $0.05 < x < 0.5$ with merely 10 polynomials and it took about a few seconds by the SUN-IPX in 1994. This method was also applicable to the small-x ($x \approx 0.01$) region if we take large number of Laguerre expansion coefficients (N=20$\sim$30), and typical accuracy at x=0.01 was about 10% (3%) in the spin-dependent (spin-independent) case. At intermediate x ($0.05 < x < 0.5$), the accuracy was much better. However, they were worse at large x ($x > 0.8$) where structure functions are very small so that it may not be serious problem practically. Because the 10% inaccuracy at $x = 0.01 \sim 0.02$ changed the integral $\int_{0.01}^{1} dx g_1(x)$ only 0.2%, the Laguerre method can be used to investigate spin-dependent structure functions at small x, as long as it is not too small ($x < 0.01$). Therefore, although the accuracies are not good in the very small and very large x regions, it can be used as an effective and accurate method in the "practical" x region.

Second, the Euler's method was used for solving the DGLAP and Mueller-Qiu evolution equations for the nucleons and nuclei. In this method, the variables x and Q^2 were simply divided into small steps to calculate the differentiations and integrals, and it can improve the precision issue at small and large x of the Laguerre method. Numerical results indicated that the accuracy is better than 2% in the region $10^{-4} < x < 0.8$ if more than two-hundred Q^2 steps and more than one-thousand x steps are taken. The numerical solution was discussed in detail, and evolution results were compared with Q^2 dependent data in CDHSW, SLAC, BCDMS, EMC, NMC, Fermilab-E665, ZEUS, and H1 experiments. We provided a FORTRAN program for Q^2 evolution (and "devolution") of nonsinglet-quark, singlet-quark, $q_i + \bar{q}_i$, and gluon distributions (and corresponding structure functions) in the nucleon and in nuclei.

These studies were extended to the longitudinally polarized [52] and transversity evolution equations [51]. In the longitudinal-polarization studies, Q^2 variations of the polarized structure function g_1 and the spin asymmetry A_1 were investigated in both LO and NLO for specifying the NLO effects. At that time, analysis groups obtained g_1 often by neglecting the Q^2 dependence in the asymmetry A_1. However, we pointed out that it is inappropriate because clear Q^2 dependence existed especially in the small Q^2 region ($Q^2 < 2$ GeV^2). For a precise determination of g_1, the Q^2 dependence of A_1 needs to be taken into account properly. Furthermore, we investigated the numerical solution for the transversity distributions (h_1 or $\Delta_T q$) [51], as explained in the topic item 35. We supplied these Q^2 evolution codes on our web, so that other scientists could use them for their own studies.

40. Flavor asymmetric antiquark distributions $\bar{u} - \bar{d}$, $(\bar{u} + \bar{d})/2 - \bar{s}$

Light antiquark distributions were expected to be flavor symmetric because they are considered to be created mainly through perturbative QCD splitting processes from a gluon ($g \rightarrow q\bar{q}$). However, it became clear that they are not flavor symmetric from experiments. The strange-quark distribution is about a half of the up and down antiquark distributions $[(\bar{u} + \bar{d})/2 \sim \bar{s}]$ from neutrino-induced opposite-sign dimuon measurements. The inequality $\bar{u} \neq \bar{d}$ also became obvious from the NMC (New Muon Collaboration) finding on the Gottfried-sum-rule violation and Fermilab Drell-Yan experiments. The flavor asymmetric antiquark distribution $\bar{u} - \bar{d}$, created in perturbative QCD, originates from next-to-leading-order effects, so that it is much smaller than the NMC finding on $\bar{u} - \bar{d}$ in the region $Q^2 \geq 4$ GeV^2. Therefore, the flavor asymmetric antiquark distributions should come mainly from nonperturbative mechanisms.

As such a nonperturbative mechanism, we investigated meson-cloud effects on the antiquark distribution of the nucleon. First, the parameter in the pion-cloud model was fixed by the flavor asymmetric antiquark distribution $(\bar{u} + \bar{d})/2 - \bar{s}$ for predicting the $SU(2)$ flavor asymmetric distribution $\bar{u} - \bar{d}$. In the pion-cloud model, there exists a momentum cutoff parameter in the πNN form factor. This cutoff was determined by the experimental information on $(\bar{u} + \bar{d})/2 - \bar{s}$, actually a typical parametrization (HMRS) on antiquark distributions, and we found the cutoff Λ_1 of about 0.7 GeV for a monopole πNN form factor. A typical πNN form factor with Λ_1 ~0.6 GeV in quark models could be consistent with this result; however, it is softer than the πNN form factor with Λ_1 ~1 GeV widely used in nuclear physics. In particular, it is much softer than the hard cutoff of 1.4 GeV used in one-pion-exchange potentials. Then, fixing the cutoff parameter by the distribution $(\bar{u}+\bar{d})/2-\bar{s}$, we predicted $SU(2)$ flavor asymmetric distribution $\bar{u}-\bar{d}$ theoretically [68]. In 1991, the NMC indicated that the $\bar{u}$ distribution is different from $\bar{d}$ from the Gottfried-sum-rule violation. I found that the pionic contribution to the deviation from the Gottfried sum rule is around -0.04 ($\int dx(\bar{u}-\bar{d}) = -0.06$) [67,68]. This value corresponds to about 1/2 of the the discrepancy found by the NMC, so that the order of magnitude of the NMC finding on $\bar{u}-\bar{d}$ can be understood by the pion-cloud model, in general meson-cloud models. This negative contribution was due to an excess of $\bar{d}$ over $\bar{u}$ in π^+ and it was partly cancelled by a positive contribution due to an excess of $\bar{u}$ over $\bar{d}$ in an extra π^- in the πNΔ process.

Then, various possible reasons were discussed for the Gottfried-sum-rule violation, including significant contributions from valence quarks at very small x and $SU(2)_f$ breaking in the sea. We suggested various experiments, which could give a direct measurement of $\bar{u}-\bar{d}$, including neutrino scattering and Drell-Yan measurements [53,59,65,66]. A paper was written for summarizing theoretical and experimental investigations, such as historic background, perturbative QCD effects, various hadron models, past experiments, and future prospects, on the Gottfried sum rule and the $\bar{u}-\bar{d}$ distribution [53].

41. Sum rule of tensor structure function b_1

In spin-1 hadrons, there are new structure functions, in addition to the ones (F_1, F_2, g_1, g_2) which exist for the spin-1/2 nucleons, associated with its tensor structure. In 1989, the new structure functions were named as b_1, b_2, b_3, and b_4 in charged-lepton deep inelastic scattering from a spin-one hadron such as the deuteron. Among them, twist-two functions are related by the Callan-Gross type relation $b_2 = 2xb_1$ in the Bjorken scaling limit. The functions b_3 and b_4 are higher-twist structure functions, so that we first investigated the twist-2 structure function b_1.

In our work, we derived a sum rule for b_1 by the parton model. From the parity and time-reversal invariances, the only global electromagnetic observable for a spin-1 hadron is the electric quadrupole moment, which does not exist for the spin-1/2 nucleons. Therefore, we studied the b_1 sum rule by speculating that it could be related to the electric quadrupole moment. The integral of b_1 over the Bjorken variable x was written in terms of tensor-polarized parton distribution functions (PDFs). Then, helicity amplitudes of elastic photon-hadron scattering were expressed by electric monopole and quadrupole form factors and also by the tensor-polarized PDFs. Through the tensor-polarized PDFs, the b_1 integral was then related to the electric quadrupole form factor. In this way, if antiquark distributions are not tensor polarized, the sum became $\int dx b_1(x) = \lim_{t\to 0}(5t/12)\,F_Q(t) = 0$ [69], where $F_Q(t\to 0)$ is the electric dipole moment of a spin-1 hadron. Furthermore, if the antiquark distributions are tensor polarized, we obtained the sum $\int dx\, b_1(x) = -\lim_{t\to 0}\frac{5}{24}\,t\,F_Q(t)+\sum_i e_i^2\int dx\,\delta_{_T}\bar{q}_i(x)$ [69], where $\delta_T\bar{q}(x)$ is the tensor-polarized antiquark distribution. This relation is very similar to the Gottfried sum rule with flavor-asymmetric correction term, $\int(dx/x)\,[F_2^p(x)-F_2^n(x)] = (1/3)+(2/3)\int dx\,[\bar{u}(x)-\bar{d}(x)]$.

This b_1 sum rule was investigated experimentally by the HERMES collaboration [A. Airapetian *et al.*, PRL 95 (2005) 242001], and they obtained $\int_{0.002}^{0.85} dx\, b_1(x) = \frac{1}{2}[1.05 \pm 0.34(\text{stat}) \pm 0.35(\text{sys})]\times 10^{-2}$, where the 1/2 factor is introduced so as to express b_1 per nucleon. It indicated an existence of finite tensor-polarized antiquark distributions. Since it may not be easily understood in a standard deuteron model, we need further studies on this topic. This situation is very similar to the one in the beginning of 1990's when the NMC finding on the Gottfried-sum-rule violation created the field of flavor-asymmetric antiquark distributions and their nonperturbative QCD mechanisms. A new b_1 experiment will start at JLab by the middle of 2020's and there is also experimental possibility in the Fermilab-E1039 experiment on Drell-Yan cross-section measurements, so that a possible new hadron-physics field could be created by studying the tensor-polarized structure functions.

42. Local EMC effect

    Nuclear modification of structure functions was discovered by the European Muon Collaboration (EMC), and it is called EMC effect. The nuclear structure functions have been investigated by inclusive deep inelastic lepton scattering from a nucleus. The inclusive cross sections contain information on interactions with all the constituents, and the EMC effect is an effect averaged over all nucleons in the nucleus. However, it is possible that the EMC effect depends significantly on the location of the struck constituent within the nucleus. Such effects, which we shall call "local" EMC effect, could be tested by (semi-)exclusive experiments. In order to investigate this topic, we studied the dependence of the EMC effect on nuclear structure, namely the dependence on the location of the struck quark within a nucleus. Such studies are important to investigate the local interaction information for understanding the nuclear modification mechanisms and also for application purposes. For example, the local interaction information is necessary for the J/ψ suppression phenomena, which could be considered as a signature of quark-gluon plasma formation, because heavy-ion reaction events are separated by the total transverse energy E_T for finding central and peripheral collisions.

    Therefore, we theoretically investigated the local EMC effect and discussed experimental possibilities [70]. The EMC effect was investigated by nuclear-binding model, Q^2-rescaling model, π-meson effects, and so on; however, they were studied as global effects averaged over the whole nucleus. However, there could be experiments to indicate the local effects by considering, for example, that $(e, e'p)$ reactions with a nuclear target have information on whether the proton is emitted from the $1s$ or $1p$ state in the nucleus. We investigated the local EMC effect theoretically by the nuclear-binding and Q^2-rescaling models. As a nucleus, we took ^{19}F and a density-dependent Hartree-Fock method was used for describing the nucleus. Since the EMC effect is sensitive to the nuclear binding and radius, we employed the density-dependent Hartree-Fock method which can explain these two essential factors. Using wave functions of the $1s$, $1p$, and $1d$ levels, we calculated the local EMC effects. We found that both models give similar results in the sense that the scattering from a central or deeply-bound constituent gives a larger EMC effect than the scattering from a surface or weakly-bound constituent [70]. At the stage of 1990, there were Fermilab-E745 and BEBC (Big European Bubble Chamber) experiments which would be related to the local EMC effect; however, it was not clear whether their experimental data actually showed the locality. We hope to have future experimental progress on this topic. On the other hand, the central and surface collisions are often separated in heavy-ion collisions, so that the local EMC effect could be investigated from such aspects.

43. Excitations of polarized vacuum around a large Z "nucleus"

    In 1998, there was an issue of anomalous positron peaks, which could not be explained theoretically, in low-energy uranium-uranium collisions at GSI (Gesellschaft für Schwerionenforschung) in Germany. We studied a possible explanation of the positron peaks in terms of collective excitations in Quantum Electrodynamics (QED). In this heavy-ion collision, the total electric charge is 184 because the atomic number of the uranium is 92. Since the fine structure constant of QED is small ($\alpha \simeq 1/137$), perturbative methods are usually used in solving QED problems theoretically. However, the total charge 184 is larger than $1/\alpha$, so that such perturbative QED methods cannot be used for describing the uranium-uranium collision.

We investigated this topic in a nonperturbative method by bosonizing $1+1$ dimensional QED. Here, the 1+1 dimensions mean time and one radial coordinate (r). For handling the problem theoretically, we simplified the problem by considering a large artificial nucleus with the atomic number $Z \sim 180$, and then we studied polarized-vacuum excitations around this large nucleus [77]. It is known that fermions are equivalently described by boson fields in 1+1 dimensional field theories. Using this correspondence, we bosonized the 1+1 dimensional QED. Expressing the spacial distribution of electron clouds around the nucleus by a boson field, we studied excitations from the ground state. As a result, oscillations of the electron clouds were described by two independent differential equations. Solving these equations, we found that there exist at least two stable excited states in the vacuum around the large "nucleus" in a few MeV energy region. These neutral oscillation modes decay into an electron-positron pair through electromagnetic interactions. These modes roughly corresponded to the positron energies measured at GSI, so that the anomalous GSI events could be explained by such collective excitations in QED. Later, the GSI experiments were reexamined and the anomalous positron peaks disappeared. Nonetheless, we believe that our collective QED excitations should exist, although the artificial nucleus with $Z \sim 180$ is assumed in our work, because we solved the QED problem properly by a solid nonperturbative method. We hope that such excitations will be discovered experimentally.

44. N-Δ transition quadrupole moment

There exist deformed nuclei with shapes like pancakes and cigars, and they are observed as their electric quadrupole moments. For example, the electric quadrupole moment of the deuteron is 0.29 fm^2, which indicates a small cigar-like deformation. It is known that this deformation originates from tensor interactions in nuclear forces. Therefore, it is an appropriate quantity to understand nucleon-nucleon interactions and in general properties of many-nucleon systems. On the other hand, hadron shapes were not known at the stage of 1988, although there were some theoretical suggestions. Since there are tensor interactions in the gluon-exchange potential between quarks and there is correlation between cloud pions and nucleon spin, the nucleons could be deformed. However, there is no observable like the electric quadrupole moment in the spin-1/2 nucleons to indicate the deformation, so that we may reply on the spin-3/2 Δ. We should note that the Δ lifetime is about 10^{-22} second and it cannot be used as a fixed target, so that possible experimental methods needed to be developed.

We investigated the N-Δ transition quadrupole moment in Refs. [72,74]. As explained in the studies of Δ electromagnetic moments of the topic item 47, the photon energy (E_γ <120 MeV) was not large enough to probe the electric quadrupole moment of Δ in the pion-nucleon bremsstrahlung process $\pi N \to \pi N \gamma$. The momentum transfer in the N-Δ transition is about 400 MeV, which could be large enough to probe a small quantity like the electric quadrupole moment. So, possibilities of measuring the N-Δ transition quadrupole moment were investigated. I joined in a research proposal by the N-Δ collaboration for N(e,e′π) and N(e,e′γ) experiments at the Bates Linear Accelerator Center. In particular, I showed the role of the N-Δ transition quadrupole moment theoretically [72]. The $N(e,e'\gamma)$ cross section indicated a typical dipole radiation pattern if the quadrupole moment vanishes. I showed that the $N(e,e'\gamma)$ cross section rotates from the dipole-radiation pattern if a finite quadrupole moment exists. Furthermore, it is possible to measure the quadrupole moment in the out-of-scattering plane. On the other hand, the pionic contributions to the scalar and longitudinal proton→ Δ^+ transition quadrupole moments were evaluated [74] and it was $Q^{(\pi N)}_{\Delta^+ p}\approx+0.02-i0.09$ fm^2. This value is larger than the one predicated by the tensor force in the one-gluon-exchange potential, so that experimental measurements do not directly indicate the quadrupole moment of the tensor force in the quark model.

45. Decays of mesons and baryons in a flux-tube quark model

For finding internal structure of hadrons, it is often useful to investigate hadron decays. Radiative decays are described by quark models rather easily. However, strong decays were not well studied theoretically at the stage of 1987. So, we investigated the strong decays of hadrons by the flux-tube model [71,75], which was suggested by lattice QCD. From the lattice QCD and the Regge trajectory, the linear potential was obtained as the long-range part of quark-quark interactions. It indicates that color electric fields are confined in one dimension connecting a quark and an antiquark without spreading in three dimensions. This one-dimensional color flux is called color flux tube.

First, we investigated the strong decays of mesons [75]. This work was intended to explain hadron decays by the flux-tube model and then to describe the nucleons and Δ which are important for nuclear phenomena. A $q\bar{q}$ pair, created in the one-dimensional color electric fields, is in the $^3S_1$ state. However, if the string-like color electric fields fluctuate, the angular average may be taken and the $q\bar{q}$ state becomes $^3P_0$ instead of $^3S_1$. So, using these $^3S_1$ and $^3P_0$ $q\bar{q}$ creation models within the color electric fields, we investigated strong meson decays such as $\rho\to 2\pi$ and $b_1\to\pi\omega$, especially how the decay widths depend on final-state interactions and the size of pion. We found that both $^3S_1$ and $^3P_0$ models can explain the available data; however, the $^3S_1$ model required stronger final-state interactions.

Next, this research was extended to the πNΔ system by breaking one of the flux-tubes in the nucleon with these $q\bar{q}$ creation mechanisms. The πNN and πNΔ coupling constants and form factors were derived by these flux-tube models [71]. Then, the long-range Yukawa force can be understood by this flux-tube breaking and then its attachment to another nucleon. This mechanism generates baryon decay widths and shifts their masses; thus the hadron spectroscopy in constituent quark models should be re-investigated including these mass shifts.

46. *y* scaling and quark effects in nuclear physics

The fundamental theory of strong interactions is quantum chromodynamics (QCD), so that nuclei should be described in principle by QCD in terms of quarks and gluons. In particular, significant nucleon overlap could exist in nuclei because average nucleon separations in nuclei are almost equal to the nucleon diameter; however, there is no undoubted explicit quark effect in nuclear structure and reaction phenomena. Namely, although we expect that quark effects should exist in nuclear phenomena, nuclei are described by effective degrees of freedom of nucleons and mesons without introducing quarks.

In order to understand this puzzling question, we studied nuclear observables by a simple quark model and its effective hadron model, and we compared both results to find whether there exists a conspicuous quark signature [76]. Specifically, as a simple model "nucleus", a two-hadron system bound in an overall harmonic oscillator potential was studied. The hadron-hadron problem was the antisymmetric $q^2\bar{q}^2$ model of Lenz *et al.* For comparison, an effective hadron model was defined in which the hadron-hadron interaction was given by the adiabatic potential derived from the quark model. The elastic form factor and the longitudinal response function were calculated by these models. Comparing these model results, we found that the observables do not provide striking signatures of the underlying quark dynamics, even though the hadron-hadron interactions are driven entirely by quark exchange. The y-scaling indicates that the longitudinal response function in electron-nucleus scattering is expressed solely by the distribution of the longitudinal momentum of a nucleon, $y = \hat{q} \cdot \vec{p}$. Our results indicated that the differences between the quark and hadron models are small in the longitudinal response function. Therefore, nucleon momentum distributions in nuclei should be determined accurately by using the y-scaling. Furthermore, we found in our model that a simple parametrization of modified hadron size in the bound state, motivated by the bound quark momentum distribution, is not a useful way to correlate different observables. In this way, we found that it is difficult to find the explicit quark signature in low-energy nuclear physics, and effective descriptions of nuclei in terms of hadrons are generally appropriate.

47. Δ electromagnetic moments

The spectroscopy and static properties of hadrons played a central role in the development of quark models. However, little precise information was available for baryons outside the ground state octet, since such baryons generally appear as broad resonances coupled to strong interaction decay channels. Spectroscopically, these open-channel couplings can be expected to yield dynamical mass shifts comparable to the width. Thus, the observed baryon "masses" do not directly provide a precise quantitative test of standard quark model calculations. A similar problem must arise in considering other static properties such as electromagnetic moments.

Under this situation, we investigated possible determination of Δ electromagnetic moments in the pion-nucleon bremsstrahlung [73,78]. In 1980's, people were also interested in the electric quadrupole moment of Δ, in addition to the magnetic dipole moment, because Δ was expected to be deformed due to the tensor force in gluon exchange potentials between quarks. First, we calculated the Δ electromagnetic moments by the isobar model. The same dynamics which renormalize the mass and provide the strong decay width, namely coupling to the open πN channel, also renormalize the moments. These pionic contributions to the Δ electromagnetic moments were calculated and they were $\mu(\Delta^{++}) = -0.4 + i\,0.6\,\mu_p$ and $Q(\Delta^{++}) = +0.2 + i\,0.05\,\mathrm{fm}^2$. In comparison with the SU(6)-quark-model prediction $\mu(\Delta^{++}) = 2\,\mu_p$, the pionic contribution to the magnetic dipole moment was about 25%, and the one to the electric quadrupole moment was much larger than the moment predicted by the tensor force between quarks. We showed explicitly that there exist imaginary parts in the Δ electromagnetic moments due to its unstable nature.

Next, we investigated possible values of the magnetic dipole moment $\mu_{\Delta^{++}}$ and electric quadrupole moment for explaining the cross sections of the unpolarized pion-nucleon bremsstrahlung. We found that it is not possible to find the quadrupole moment because its effects are very small on the cross sections. We also found the magnetic moment; however, a precise determination was not possible from the unpolarized measurements. So, we proposed that a polarized pion-nucleon bremsstrahlung experiment can provide a precise determination of the dipole moment. Our theoretical proposal was confirmed by the PSI (Paul Scherrer Institute) experiment and they obtained the Δ^{++} magnetic moment as $1.62\,\mu_p$ [A. Bosshard *et al.*, PRL 64 (1990) 2619].

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