I have been working in theoretical hadron and nuclear physics. My studies are classified into two categories. One is on properties of hadron resonances, and the other is on structure functions of hadrons and nuclei. I explain several results from my past works. The detailed explanation of my research history is given in my home page at https://research.kek.jp/people/kumanos/ (→ Research history).

* Properties of hadron resonances

Electromagnetic properties of unstable hadrons have been key quantities for developing hadron models. Among them, we investigated properties of the Δ resonance and exotic hadron candidates, especially $f_0(980)$, $a_0(980)$, and $\Lambda(1405)$.

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. We investigated possible determination of Δ electromagnetic moments in the pion-nucleon bremsstrahlung [1]. 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 the gluon exchange potential 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 $Q(\Delta^{++}) = +0.2 + i\,0.05\,\text{fm}^2$. Next, we predicted theoretically that accurate determination of the Δ magnetic moment can be done by the polarized pion-nucleon bremsstrahlung [1]. Based on this idea, experimentalists proposed an experiment at the Paul Scherrer Institute, and they actually determined it as $\mu_{\Delta^{++}} = 1.64\,\mu_p$ [2]. On the other hand, we found that it is not possible to find the quadrupole moment because its effects are very small on the cross sections.

[1] Pion-nucleon bremsstrahlung and Δ electromagnetic moments,
L. Heller, S. Kumano, J. C. Martinez, E. J. Moniz, Phys. Rev. C 35 (1987) 718.

[2] Polarized-target asymmetry in pion-proton bremsstrahlung at 298 MeV,
A. Bosshard *et al.*, Phys. Rev. Lett. 64 (1990) 2619.

Structure of exotic hadron candidates $f_0(980)$ and $a_0(980)$

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 [3]. They were considered as $s\bar{s}$, $K\bar{K}$ molecule, tetraquark ($qq\bar{q}\bar{q}$), or glueball (gg). 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) [4]. 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. 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.

[3] Decay of mesons in flux-tube quark model,
S. Kumano and V. R. Pandharipande, Phys. Rev. D 38 (1988) 146.
[4] Scalar mesons in ϕ radiative decay: Their implications for spectroscopy and for studies of CP violation at ϕ factories, F.E.Close, N.Isgur, and S.Kumano, Nucl. Phys. B 389 (1993) 513.

In subsequent studies, we developed this field in a different way, by using our knowledge on high-energy hadron physics, for finding internal configurations of exotic hadron candidates. We proposed to use hadron tomography by three-dimensional structure functions [5], constituent counting rule of perturbative quantum chromodynamics (QCD) [5,6,7], and differences between favored and disfavored fragmentation functions [8]. These are new ideas for examining exotic hadron candidates, and experimental studies of these proposals will be done in future.

[5] Tomography of exotic hadrons in high-energy exclusive processes,
H. Kawamura and S. Kumano, Phys. Rev. D 89 (2014) 054007.
[6] Determination of exotic hadron structure by constituent-counting rule for hard exclusive processes, H. Kawamura, S. Kumano, and T. Sekihara, Phys. Rev. D 88 (2013) 034010.
[7] Constituent-counting rule in photoproduction of hyperon resonances,
Wen-Chen Chang, S. Kumano, and T. Sekihara, Phys. Rev. D 93 (2016) 034006.
[8] Proposal for exotic-hadron search by fragmentation functions,
M. Hirai, S. Kumano, M. Oka, and K. Sudoh, Phys. Rev. D 77 (2008) 017504.

Constituent counting rule for probing exotic hadron nature

Although there have been reports on exotic hadron candidates, 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 [5,6,7]. According to the perturbative QCD, exclusive high-energy hadron reactions occur by hard gluon exchanges , and their cross sections are estimated by considering hard quark and gluon propagators. 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 and t are Mandelstam variables.

First, we investigated internal structure of hyperons and their excited states by calculating the cross section for exclusive processes, for example $\pi^- + p \to K^0 + \Lambda(1405)$, which could be measured at J-PARC. We suggested that the internal quark configuration of $\Lambda(1405)$ should be determined by the asymptotic scaling behavior of the cross section [6]. 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. Second, we analyzed the JLab-CLAS data on the photoproduction of hyperon resonances [7]. Especially, $\Lambda(1405)$ could be considered to be a $\bar{K}N$ molecule with the constituent number $n = 5$. We found that the current data are not enough to conclude the numbers of its constituent. However, it is interesting to find the tendency of the energy dependence in the constituent number. $\Lambda(1405)$ looked like a pentaquark state at lower energies, but it became a three-quark one at high energies. If $\Lambda(1405)$ is a mixture of three-quark and five-quark states, the energy dependence could be valuable for finding its composition and mixture.

* Structure functions

Since 1988, I have been investigating hadron and nuclear structure functions. In the following, I explain some results.

Sum rule for the tensor-polarized structure function b_1

In spin-1 hadrons, there are new structure functions, in addition to the ones of the spin-1/2 nucleons, and one of them is the twist-2 structure function b_1. It will be measured at JLab in the middle of 2020's. In our work, we derived a sum rule for b_1 by the parton model [9]. 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, and we obtained $\int dx\, b_1(x) = -\lim_{t\to 0} \frac{5}{24}\, t\, F_Q(t) + \sum_i e_i^2 \int dx\, \delta_T \bar{q}_i(x)$, where $F_Q(t)$ is the electric quadrupole form factor of the hadron, and $\delta_T \bar{q}_i$ is the tensor-polarized antiquark distribution. The first term vanishes, so that a finite sum of b_1 indicates a finite tensor-polarized antiquark distribution. The vanishing first term comes from the fact that the valence-quark number does not depend on the tensor polarization, whereas it depends on the flavor in the Gottfried sum (1/3). This b_1 sum rule was investigated experimentally by the HERMES collaboration [10] 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. In 2017, b_1 was calculated in a standard deuteron model [11] and the obtained b_1 was very different from the HERMES data. It indicates a new hadronic mechanism in the deuteron beyond the simple bound system of a proton and a neutron.

[9] A sum rule for the spin dependent structure function $b_1(x)$ for spin one hadrons,
F. E. Close and S. Kumano, Phys. Rev. D 42 (1990) 2377.
[10] Measurement of the tensor structure function b_1 of the deuteron,
A. Airapetian *et al.*, Phys. Rev. Lett. 95 (2005) 242001.
[11] Tensor-polarized structure function b_1 in standard convolution description of deuteron,
W. Cosyn, Yu-Bing Dong, S. Kumano, and M. Sargsian, Phys. Rev. D 95 (2017) 074036.

Anomalous dimensions of chiral-odd structure function h_1

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 leading-twist structure function h_1, which is also called the quark transversity distribution $\Delta_T q$. 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 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 [12]. In order to study h_1 in QCD, we needed to introduce a set of local operators $O^{\nu\mu_1\cdots\mu_n} = S_n \overline{\psi}\, i\,\gamma_5\, \sigma^{\nu\mu_1}\, iD^{\mu_2} \cdots iD^{\mu_n}\, \psi$ $(n = 1, 2, ...)$. 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. 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 these studies, it became possible to investigate h_1 in the NLO level. We also provided a useful code for calculating this Q^2 evolution [13].

[12] Two-loop anomalous dimensions for the structure function h_1,
S. Kumano and M. Miyama, Phys. Rev. D 56 (1997) R2504.

[13] Numerical solution of Q^2 evolution equation for the transversity distribution $\Delta_T q$,
M. Hirai, S. Kumano, and M. Miyama, Comput. Phys. Commun. 111 (1998) 150.

Flavor asymmetric antiquark distributions

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 ($g \to q\bar{q}$). 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 New-Muon-Collaboration (NMC) 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. Therefore, the flavor asymmetric antiquark distributions should come mainly from a nonperturbative mechanism.

As such a nonperturbative mechanism, we investigated meson-cloud effects on the antiquark distributions of the nucleon. In the pion-cloud model, there exists a momentum cutoff parameter in the πNN form factor. Fixing this parameter by the distribution $(\bar{u} + \bar{d})/2 - \bar{s}$, we predicted the flavor asymmetric distribution $\bar{u} - \bar{d}$ theoretically [14]. We found that the order of magnitude of the NMC finding on $\bar{u} - \bar{d}$ can be understood by this pion-cloud contribution. The 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. In 1998, 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 [15].

[14] πNN form factor for explaining sea quark distributions in the nucleon,
S. Kumano, Phys. Rev. D 43 (1991) 59 & 3067.

[15] Flavor asymmetry of anti-quark distributions in the nucleon,
S. Kumano, Phys. Rept. 303 (1998) 183.

Global analyses of parton distribution functions and fragmentation functions

One of major achievements is on nuclear parton distribution functions (NPDFs). 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 NPDFs are needed. 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 $\sigma_{DY}^A/\sigma_{DY}^{A'}$. We proposed this global χ^2 method on the NPDFs for the first time in the 2001 paper [16]. The analyses were done in the leading order (LO) [16,17] and next-to-leading order (NLO) [18] 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 [17,18], so that we can discuss the NLO improvement on the determination. 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. Codes were provided for calculating the NPDFs and their uncertainties at given x and Q^2 in the LO and NLO. The 2007 version of our NPDFs was widely used as one of the standard NPDFs for a long time. In the similar way, we studied global analyses of longitudinally polarized PDFs [19] and fragmentation functions [20], and created useful codes for calculating them at given x and Q^2.

[16] Determination of nuclear parton distributions,
M. Hirai, S. Kumano, and M. Miyama, Phys. Rev. D 64 (2001) 034003.

[17] Nuclear parton distribution functions and their uncertainties,
M. Hirai, S. Kumano, and T.-H. Nagai, Phys. Rev. C 70 (2004) 044905.

[18] Determination of nuclear parton distribution functions and their uncertainties in next-to -leading order, M. Hirai, S. Kumano, and T.-H. Nagai, Phys. Rev. C 76 (2007) 065207.

[19] Global analyses of polarized PDFs: Y. Goto *et al.*, Phys. Rev. D 62 (2000) 034017;
M. Hirai, S. Kumano, and N. Saito, Phys. Rev. D 69 (2004) 054021; D 74 (2006) 014015;
M. Hirai and S. Kumano, Nucl. Phys. B 813 (2009) 106.

[20] Global analyses of fragmentation functions: M. Hirai, S. Kumano, T.-H. Nagai, and K. Sudoh, Phys. Rev. D 75 (2007) 094009; M. Hirai, H. Kawamura, S. Kumano, and K. Saito, PTEP 2016 (2016) 113B04; N. Sato *et al.*, Phys. Rev. D 94 (2016) 114004.

Gravitational form factors of a hadron

Since gravitational interactions are too weak to be measured in microscopic systems, the measurement of the gravitational form factors used to be considered impossible for hadrons and nuclei. However, we know generalized parton distributions (GPDs) and generalized distribution amplitudes (GDAs) contain matrix elements of energy-momentum tensor, which is a source of gravity within a hadron. Here, the GDAs are s-t crossed quantities of the GPDs, so that they could be called timelike GPDs. The spacelike GPDs are measured in virtual Compton scattering at lepton-accelerator facilities, but it is also possible to investigate them by using exclusive hadron reactions at hadron-accelerator facilities [21]. We extracted the gravitational form factors for the first time from actual experimental measurements [22]. 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. The GDAs were expressed by a number of parameters and they were determined from the data of $\gamma^*\gamma \to \pi^0\pi^0$. 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. 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 [22]. 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. 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 [23] was selected one of highlight research results of KEK in the annual report of 2019.

[21] GPDs at hadron-accelerator facilities: S. Kumano, M. Strikman, and K. Sudoh, Phys. Rev. D 80 (2009) 074003; T. Sawada *et al.*, Phys. Rev. D 93 (2016) 114034.

[22] Hadron tomography by generalized distribution amplitudes in pion-pair production process $\gamma^*\gamma \to \pi^0\pi^0$ and gravitational form factors for pion, S. Kumano, Qin-Tao Song, and O. V. Teryaev, Phys. Rev. D 97 (2018) 014020.

[23] Gluon transversity in polarized proton-deuteron Drell-Yan process,
S. Kumano and Qin-Tao Song, Phys. Rev. D 101 (2020) 054011; 094013.

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 [24]. 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 was no 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. Among them, 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, $\int d^2k_T h_{LT} = \int d^2k_T h_{LL} = \int d^2k_T h_{3LL} = 0$. 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.

[24] Transverse-momentum-dependent parton distribution functions up to twist 4 for spin-1 hadrons, S. Kumano and Qin-Tao Song, Phys. Rev. D 103 (2021) 014025.