SAGA-HE-135-98 (hep-ph/9806333) May 27, 1998

Studies of structure functions at a low-energy facility

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Talk given at the Workshop on
"Future Plan at RCNP"

Osaka, Japan, March 9 – 10, 1998
(talk on Mar. 9, 1998)

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Information on their research is available at http://www.cc.saga-u.ac.jp/saga-u/riko/physics/quantum1/structure.html.

to be published in proceedings

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Abstract

We discuss the studies on structure functions at the possible future RCNP facility. At this stage, an electron-proton or proton-proton collider with $\sqrt{s} = 5 \sim 10$ GeV is considered. We explain large-x physics, nuclear modification of sea-quark and gluon distributions, and tensor spin structure function as the interesting topics at the facility. The large-x parton distributions are important for finding new physics beyond QCD in anomalous events such as the CDF jet data. The nuclear parton distributions are valuable in detecting a quark-gluon signature in heavy-ion reactions. The tensor structure function b_1 is a new field of high-energy spin physics. Considering these physics possibilities, we believe that the possible RCNP facility is important for the hadron-structure community.

1 Introduction

The purpose of this talk is to discuss interesting topics which could be investigated by the possible future RCNP (Research Center for Nuclear Physics) facility in the field of structure functions. At this stage, we consider a collider with 10 GeV electron and a few GeV proton or the one with a few GeV proton and a few GeV proton (or nucleus), so that the center-of-mass energy is $\sqrt{s} = 5 \sim 10$ GeV. However, the energy range could vary depending on the physics interest.

Structure functions in the nucleon have been investigated since the 1960s through various high-energy lepton and hadron scattering processes. Now the unpolarized parton distributions are relatively well known from very small x ($\sim 10^{-5}$) to large x except for the gluon distribution at very small x and at large x. As primary future projects, high-energy facilities are discussed for measuring the polarized structure functions such as the RHIC (Relativistic Heavy Ion Collider) and the polarized HERA (Hadron-Electron Ring Accelerator). Because the energy at the future RCNP facility is expected to be much smaller than these US and European facilities, we should focus on the large-x part.

The Bjorken x is related to the square of the momentum transfer q ($q^2 = -Q^2$) as $x = Q^2/(2p \cdot q)$, where p is the proton momentum. Using the variable $y = p \cdot q/(p \cdot k)$ with the initial electron momentum k, we rewrite the relation as $x = Q^2/(2yp \cdot k) \approx Q^2/(ys)$ with $s = (p+k)^2$. In order to be deep inelastic scattering, Q^2 has to be large enough: typically $Q^2 > 1$ GeV^2. If the c.m. energy is $\sqrt{s} = 10$ GeV, the minimum x is then given by $x_{min} \sim 1/(10)^2 = 0.01$. The x region ($0.01 < x < 1$) is considered as a "large"-x one in comparison with the HERA kinematical range ($x_{min} \sim 10^{-5}$). Therefore, we should find interesting topics in this large-x region. Even though this region has been investigated for a long time, there are still important issues. In particular, if accurate experimental data are taken, the large-x could be more important than the small-x part which has been paid attention to in the last several years. The large-x parton distributions have not been measured accurately at the existing facilities; however, they are essential, for example, in explaining the CDF anomalous jet events. In this sense, a rather low-energy but high-intensity accelerator is crucial for finding new physics beyond quantum chromodynamics (QCD). We discuss the importance of large-x physics in section 2.

The European Muon Collaboration (EMC) experimental results in 1983 shed light on nuclear modification of the parton distributions. The modification mechanisms of the structure function F_2 were studied in the medium-x region for explaining the EMC results. Then, the small-x region was investigated as nuclear shadowing. Now, the details of the F_2 modification are known from small x to large x. However, nuclear sea-quark and gluon distributions are not well determined even though they are important for applications to high-energy heavy-ion physics. We discuss interesting nuclear parton distributions and whether they could be measured at the low-energy facility in section 3.

The last topic is on spin-dependent structure functions. Those for the spin-1/2 proton have been studied particularly in the last ten years. Now, the g_1 structure functions have been measured by several experimental groups, and we have rough idea on the longitudinally polarized parton distributions. The missing parts in the proton are the transversity structure function h_1 and higher-twist ones. Because there are other future projects to study these spin-1/2 structure functions, we had better consider another direction in the field of spin physics. One of the possible ideas is to investigate new structure functions for spin-one particles. It is known that there is a new twist-two structure function b_1, which does not exist for spin-1/2 particles, for example in the electron-deuteron scattering. Although the HERMES collaboration will report on b_1 in the near future, we do not think that the results are accurate enough to find the small quantity. The Electron Laboratory For Europe (ELFE) is a suitable facility; however, the project is not materialized yet. Considering these situations, the future RCNP facility could be the first one to measure b_1 if it is approved in the near future. We discuss this point in section 4.

The above topics are important for finding new physics at very high-energy accelerators, for detecting a quark-gluon plasma signature, and for creating a new field of high-energy spin physics. Therefore, the future RCNP facility should be valuable in the hadron-physics community. In the following sections, we discuss the details of each topic.

2 Large-x physics for finding a signature beyond QCD

We may think that the medium and large x physics has been already investigated extensively and that no interesting physics is left. It may be right in the sense that a lot of experimental data exist; however, if a high-intensity facility is built, the situation could be different. In order to convince that the large x is important, we discuss well-known CDF (Collider Detector at Fermilab) anomalous jet events as an interesting example and their relation to the large-x gluon distribution.

The CDF collaboration measured the inclusive jet cross sections in the $p+\bar{p}$ reaction with $\sqrt{s}$ = 1.8 TeV. The measured cross sections agree, in general, with the next-to-leading-order (NLO) QCD calculation. However, they found significant differences from the NLO prediction in the large jet transverse-energy region, E_T > 300 GeV [1]. In Fig. 1 of Ref. [1], they show the fractional difference from the NLO calculation with the MRS-D0$'$ input distribution. They also show theoretical predications with different parton distributions: MRSA$'$, MRSG, CTEQ2M, CTEQ2ML, and GRV-94. Even though the theoretical cross sections depend on the distribution model, the variations are within about 10%. On the other hand, the CDF data deviate about 30% in the large E_T region. It was thought to be much larger than theoretical ambiguities.

Because this is the unexplored kinematical region, people speculated exotic mechanisms such as subquark. However, it became clear later according to the CTEQ collaboration [2] that the anomalous jet events could be explained if the gluon distribution is significantly larger than the CTEQ2M and CTEQ3M distributions at x > 0.4. In Fig. 1, the CTEQ3M and CTEQ4HJ parton distributions are shown by the dotted and solid curves, respectively. It is obvious from the figure that the quark and antiquark distributions are essentially the same in the

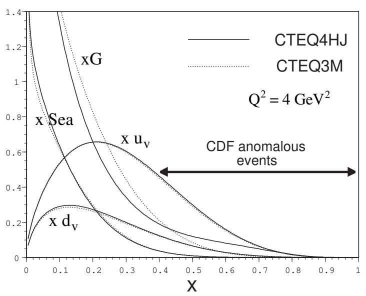

Figure 1: The CTEQ3M and CTEQ4HJ parton distributions at Q^2=4 GeV^2.

two parametrizations. However, the gluon distributions differ significantly. The CDF events are taken at large E_T so that the distributions should be evolved to the scale $Q^2 = (E_T/2)^2$. In the central rapidity region, the contributing partons have the fraction of momentum, $x_{1,2} \sim 2E_T/\sqrt{s}$. Substituting $\sqrt{s} = 1.8$ TeV and for example $E_T \sim 350$ GeV, we obtain $x_{1,2} \sim 0.4$. The major subprocesses at such a large E_T are quark-quark and quark-gluon interactions, so that the parton distributions should be supplied at large x and large Q^2. The standard way is to use the parton distributions, which are optimized so as to explain many other experimental data, then to evolve them to large Q^2 by using the DGLAP equations:

$$\frac{\partial}{\partial(ln\,Q^2)}\,q(x,Q^2) = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dy}{y}\;\left[\,P_{qq}(x/y)\,q(y,Q^2) + \;P_{qG}(x/y)\,G(y,Q^2)\right]\;,$$

$$\frac{\partial}{\partial(ln\,Q^2)}\,G(x,Q^2) = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dy}{y}\;\left[\,P_{Gq}(x/y)\,q(y,Q^2) + P_{GG}(x/y)\,G(y,Q^2)\right]\;. \quad (1)$$

According to these evolution equations, the parton distributions in the x region, $0.4 \le x \le 1$, should be known at a certain low Q^2 in order to calculate those distributions at very large Q^2 $(= E_T^2/4)$. However, the gluon distribution in this x region is not known at all as obvious from Fig. 1, where the CTEQ4HJ gluon distribution is much larger than the CTEQ3M one. It should be noted that the CTEQ4HJ is in the perfect agreement with the CDF data on the contrary to the CTEQ3M.

In this way, we find that the large-x gluon distribution is essential for determining whether or not the CDF events are really anomalous. At this stage, there is no way to fix the gluon distribution at such a large x. In order to confirm the conservative CTEQ explanation, we have to measure the gluon distribution. Although the high-energy accelerator is suitable for studying the small x distributions, the low-energy facility like the future RCNP is valuable for the large-x measurements. We should be, however, careful that the intensity is high enough to find small quantities. The large-x gluon distribution could be probed by the direct photon process in Fig. 2, but the details should be studied on higher-order corrections (K-factor), higher-twist effects, possible photon background, and expected hard-photon p_T distribution. Because the RCNP energy is not fixed yet, we may study the optimum one for measuring the gluon distribution in the direct photon process. The c.m. energy $\sqrt{s} \sim 10$ GeV may not be large enough for the direct photon process.

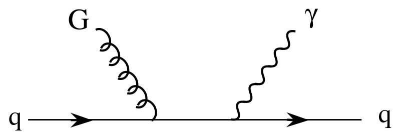

Figure 2: Direct photon process for finding the large-x gluon distribution.

3 Parton distributions in nuclei

The parton distributions are modified in the nuclear environment, and the modification is well investigated through the structure function F_2. As an example, the ratio F_2^{Ca}/F_2^D is shown in Fig. 3, where the SLAC-E139, New Muon Collaboration (NMC), and Fermilab-E665 data are included [3]. The F_2 structure function has been measured also for various size nuclei. The large-x region ($x > 0.7$) is usually attributed to the nucleon Fermi motion in the nucleus, the medium-x to the binding mechanism and confinement-radius change, and the small-x to the nuclear shadowing. It is not the purpose of this paper to discuss the details of these mechanisms, so that the interested reader may read a summary paper [4] or a recent report [5].

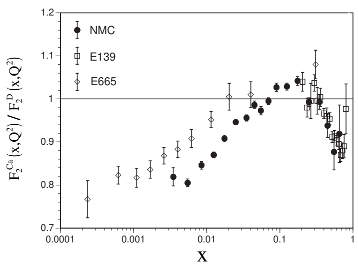

Figure 3: Experimental data for F_2^{Ca}/F_2^D.

Although there are some differences between the NMC and E665 data, the structure functions F_2^A have been rather well studied from very small x to large x. The RCNP energy range is, at least at this stage, close to the one for the fixed target experiments at SLAC. Because the SLAC group has done the extensive studies of nuclear F_2, we had better think about other possibilities. To know the F_2 structure function in a nucleus does not mean that all the parton distributions are known in the nucleus. The F_2 structure function is given by $F_2 = x\sum_i e_i^2(q_i + \bar{q}_i)$. It is dominated by the sea-quark distributions at small x ($x < 0.01$) and by the valence-quark ones at large x ($x > 0.3$). This fact means that the sea (valence) quark modification at small (large) x is known from the F_2 measurements. However, the modification of the valence and sea quark distributions is not known in the whole-x range. The sea-quark distributions in the proton are determined by using various experimental data such as electron/muon deep inelastic scattering, neutrino scattering, Drell-Yan process, and W production cross sections. In the nuclear case, a variety of these experimental data are not available at this stage, so that the precise determination of each quark/antiquark distribution is not possible.

Considering the above situation, we think that the interesting future direction is to separate valence and sea quark distributions. Then, each flavor distribution should be also determined. Furthermore, it is noteworthy that little is known for the gluon distributions in nuclei although they play a major role in high-energy heavy-ion reactions. As an example of model predictions, we show the sea-quark and gluon distributions for the nuclei He, C, Ca, and Sn in Figs. 4 and 5. The distributions are calculated at $Q^2 = 5$ GeV^2 in a parton model with Q^2

rescaling and parton-recombination mechanisms [5]. The model parameters are determined so that the theoretical ratio agrees with the F_2^{Ca}/F_2^D data. For the details of the model, the reader is suggested to read Ref. [5]. Here, the rescaling model is employed as an effective model which includes the binding-type nuclear effects and confinement-size modification, and the recombination model is as a shadowing model in an infinite momentum frame.

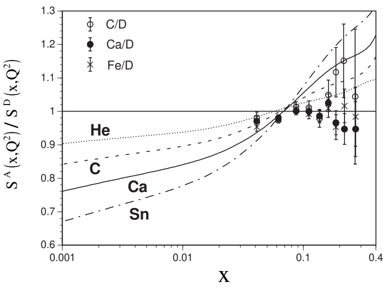

Figure 4: Sea-quark distributions in nuclei.

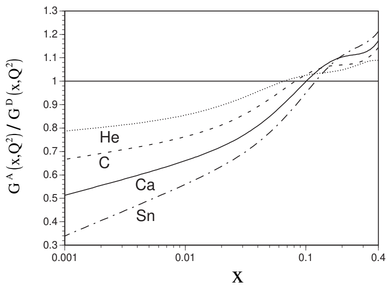

Figure 5: Gluon distributions in nuclei.

Because the future RCNP cannot compete with other high-energy facilities in the small-x physics, we should think about possible physics in the x region, $x > 0.05$. The sea-quark shadowing becomes conspicuous in the x region, $x < 0.01$, so that higher energy facility should be appropriate for measuring the sea shadowing. In fact, it will be investigated at RHIC. The E772 Drell-Yan data [6] are also shown in Fig. 4. Although the iron data are often quoted in suggesting that there is no sea-quark modification in the $x \sim 0.1$ region, the situation is not so clear: the carbon data lie above the unity and the calcium data are below. It is hard to believe this kind of A dependence. Because the sea-quark distribution itself is very small at $x > 0.2$, the experimental errors become large. Fortunately, this region is just the kinematical range of the future RCNP facility. If it has enough intensity, it should be possible to measure the sea modification in detail, particularly the A dependence. Because the sea-quark distribution in this x range cannot be determined by F_2, we should rely on the Drell-Yan process $p + A \rightarrow \mu^+\mu^- + X$ for various nuclei. The accurate measurements should clarify theoretical issues. For example, although it is not explicitly included in the above model, the sea-quark enhancement is generally predicted in the pion-excess model in contradiction to the E772 iron data. Therefore, future RCNP data could shed light on the pion-excess mechanism, namely on the nuclear force. The accurate data will be valuable also for determining the nuclear parton distributions in the whole-x range.

The prediction for the nuclear gluon distribution is shown in Fig. 5. Although there are implicit data on the gluon modification, there is no accurate explicit data at this stage. The gluon shadowing takes place at $x \sim 0.1$ and it becomes conspicuous at $x \sim 0.01$. Since the gluon shadowing will be investigated also at RHIC, the future RCNP may address the region $x > 0.1$. In the nucleon case, the scaling violation of F_2, direct-photon process, and J/ψ production are used for determining its gluon distribution. The wide range of scaling violation data and the significant J/ψ events would not be obtained at the RCNP, so that the remaining possibility is to use the direct photon process. It has been already discussed in section 2. Because there may exist complexities due to the available low energy, we should study the reaction in detail.

If the nuclear sea-quark and gluon distributions are obtained at the future RCNP in the x range, $x > 0.1$, they should be valuable not only for establishing the theoretical nuclear model but also for applications to high-energy heavy-ion physics. In particular, we believe that the accurate nuclear parton distributions are essential for finding a quark-gluon plasma signature. For example, although the J/ψ production may be related to such a signature, its cross section is not precisely calculated at this stage due to the lack of information on the nuclear gluon distributions.

4 Polarized parton distributions

Spin-dependent structure functions are studied for the proton and for the "neutron". Now, there are many data on the structure function g_1. However, as the F_2 measurements could not fix the valence and sea quark distributions in section 3, each polarized distribution cannot be determined solely by the g_1 data. Therefore, we have to wait for future measurements to solve the proton spin issue completely [7]. As it was explained in section 2, the large-x unpolarized distributions could be studied at the future RCNP. In the same way, the polarized distributions at large x should be important for finding an exotic signature in polarized reactions. It could be one of the interesting topics on spin physics at the facility. However, there are future plans and proposals at BNL, CERN, DESY, and SLAC on the polarized parton distributions for the spin-1/2 nucleon, so that we had better focus on a different spin topic. One of the other possibilities is to investigate a new spin-dependent structure function b_1 in the spin-one hadrons.

The polarized deuteron is used for measuring the g_1 structure function of the neutron. Because the deuteron is a spin-one hadron, there should exist extra spin-dependent structure functions. These are named b_1, b_2, b_3, and b_4 [8]. Because the twist-two ones are related by the Callan-Gross type relation $b_2 = 2xb_1$ in the leading order, the essential part is to study b_1 or b_2. It is also interesting to investigate a quadrupole sum rule for b_1 [9]. The b_3 and b_4 are higher-twist structure functions, so that it is not worth while discussing the details at this stage. These structure functions are defined in the hadron tensor $W_{\mu\nu}$ in the polarized electron-deuteron reaction; however, the expression is too lengthy to write it down here. The reader may look at Ref. [8] or [10].

The b_1 structure function is discussed within the context of the ELFE proposal in Ref. [10]. If the RCNP facility is intense enough, it could be used for measuring b_1 which is expected to be very small. In order to measure b_1, the electron does not have to be polarized. It is related to the polarized cross sections by

$$b_1 \propto d\sigma(0) - \frac{d\sigma(+1) + d\sigma(-1)}{2} \ , \tag{2}$$

where $d\sigma(H)$ indicates the electron-deuteron cross section with the z-component H of the target spin. Combining the cross sections with a target polarized parallel (and antiparallel) to the lepton beam direction with the unpolarized cross section, we obtain b_1. It can be expressed also in the parton model. Calculating the cross sections in a parton model, we have the expression

$$\begin{aligned} b_1(x) \ &= \sum_i e_i^2 \, [\, \delta q_i(x) + \delta \bar{q}_i(x) \,] \ , \\ \delta q_i(x) \ &= \ q^0_{\uparrow i}(x) - \frac{1}{2}[q^{+1}_{\uparrow i}(x) + q^{-1}_{\uparrow i}(x)] \ = \ \frac{1}{2}[q^0_i(x) - q^{+1}_i(x)] \ , \end{aligned} \tag{3}$$

where the superscript indicates the hadron helicity in an infinite momentum frame.

As it is obvious from Eqs. (2) and (3), b_1 is related to the tensor structure of the deuteron. It is well known that the D-state admixture gives rise to the finite quadrupole moment of the deuteron. The b_1 structure is related to such physics. Of course, the deep inelastic process is under consideration right now, so that the electric quadrupole structure probed by b_1 could be very different from ordinary low-energy results. In this sense, b_1 is a suitable structure function which could indicate "exotic components" of the hadron structure.

There is an interesting point on the sum rule. The Gottfried sum rule has been studied well last several years, and its failure resulted in revealing the light antiquark flavor asymmetry. A similar sum rule exists for b_1 according to Ref. [9]. The similarity is obvious if they are written together:

Gottfried:

$$\int dx \, [F_2^p(x) - F_2^n(x)] = \frac{1}{3} \qquad\qquad + \ \frac{2}{3} \int dx \, [\, \bar{u}(x) - \bar{d}(x) \,] \ , \tag{4}$$

Ref. [9]:

$$\int dx \, b_1(x) = \lim_{t \to 0} \ - \frac{5}{3} \frac{t}{4M^2} F_Q(t) \ \ + \ \frac{1}{9} \, \delta Q_{sea} \ , \tag{5}$$

where δQ_{sea} is the sea-quark tensor polarization, for example $\delta Q_{sea} = \int dx[8\delta\bar{u}(x)+2\delta\bar{d}(x)+\delta s(x)+\delta\bar{s}(x)]$ for the deuteron, and $F_Q(t=0)$ is the quadrupole moment in the unit of e/M^2 for a spin-one hadron with the mass M. As it is shown in Eqs. (4) and (5), there are following similarities. Because the valence-quark number depends on flavor, the finite sum 1/3 is obtained in the Gottfried sum rule. However, the first term vanishes in the b_1 case, which reflects the fact that the valence number does not depend on spin. The second term in Eq. (5) corresponds to $\int dx(\bar{u}-\bar{d})$ in Eq. (4). If a deviation from the sum $\int dx b_1(x) = 0$ is found, it should suggest a finite sea-quark tensor polarization as the Gottfried-sum-rule violation suggested a finite $\bar{u}-\bar{d}$ distribution.

The theoretical study of b_1 is still at the preliminary stage, and there exists no experimental data. The HERMES collaboration will report on b_1 in a few years. However, because the b_1 is expected to be very small, $b_1/F_1 \sim 0.01$ in a naive quark model for the deuteron [10], they would not be able to measure it. It may be possible at ELFE, but the facility itself is not approved yet. If the RCNP facility will be built in the near future, it could be the first one to measure the tensor structure function b_1. This is a new field of high-energy spin physics so that unexpected experimental results could be obtained. The studies on the new spin structure are important for testing our knowledge of high-energy spin physics in the unexplored field and for establishing the hadron structure model in the high-energy region.

5 Summary

We have discussed the studies of structure functions at the possible future RCNP facility, which is considered as a "low-energy" facility in comparison with those at BNL, CERN, DESY, and Fermilab. First, we focused on the large-x part of parton distributions. Explaining the CDF anomalous events and their relation to the large-x parton distributions, we concluded that the large-x physics is important for finding new physics beyond quantum chromodynamics. A rather low-energy machine with high intensity is suitable for measuring the parton distributions at large x. Second, possible studies on nuclear parton distributions were discussed. In particular, modification of sea-quark and gluon distributions is not well known although it is important for finding the quark-gluon plasma signature. Third, spin-dependent structure functions were discussed. The large-x part could be also studied in the same way as the unpolarized case; however, the tensor structure function b_1 should be an interesting one as a new topic in high-energy spin physics. From these discussions, we think that it is worth while proposing the new RCNP facility.

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Information on their research is available at http://www.cc.saga-u.ac.jp/saga-u /riko/physics/quantum1/structure.html.

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