Heavy Quark Productions with Spin

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Abstract

Heavy quark productions in high energy polarized scatterings are reviewed from a personal point of view. After mentioning why heavy quark physics is so interesting, I concentrate on two rather specific subjects: (1) polarized $\Lambda^+_c$ productions in deep inelastic $\ell p$ scatterings and (2) $\psi'$ productions in polarized $pp$ collisions. The first one is an interesting process for extracting the polarized gluon in the proton and the second one may give another test of the color-octet model of heavy quarkonium productions in high energy collisions.

1. Why heavy quarks?

Quantum Chromodynamics (QCD) is the underlying field theory of strong interactions of quarks and gluons. Although it is surprisingly successful in describing physics in perturbative regions, it is not so easy task to directly apply QCD for nonperturbative regions because of its complicated structure. To understand physics of quarks and gluons, it is not enough to write down the QCD Lagrangian. The more important thing is to study how quarks and gluons interact to make hadrons and how they are produced in high energy collisions.

So far, to understand the complicated structure of hadron dynamics in nonperturbative regions, many effective theories such as the potential model, the chiral perturbation theory, the Skyrme model, the Bag model, the heavy quark effective theory (HQET) and so on, have been proposed. These theories have their own scales in which they work. Here I would like to just mention an important role of mass hierarchy and scale. At present, we have 6 quark flavors, $u, d, s, c, b,$ and $t$, whose masses are arranged, in order, from light to heavy quarks. Among them, the masses of $u, d$ and $s$ quarks are smaller than the QCD scale $\Lambda_{QCD} \approx 200 MeV$ and the SU(3) flavor symmetry is approximately realized as a good symmetry. Chiral dynamics works well for these light quarks and can be applied for parameters remaining to be constant when $m_q \to 0$. Actually $m_q$ is not 0 and we have symmetry breaking due to $m_q/\Lambda_{QCD}$. On the other hand, the heavy quark effective theory (HQET) works well for the $c$ and $b$ quarks which are much heavier than the $\Lambda_{QCD}$ value. For hadrons containing these quarks, the heavy quark spin interaction decouples from QCD interactions and thus the SU(2$N_f$) spin-flavor symmetry appears as a good symmetry. The HQET can be applied for parameters remaining to be constant when $m_Q \to \infty$. Since $m_Q$ is actually not infinite, we have symmetry breaking due to $\Lambda_{QCD}/m_Q$. Practically, the HQET can not be applied for hadrons including a top quark. The top quark is very special because it is extremely heavy: it is much heavier than the $W$ boson with $m_W \approx 80 GeV$. A top quark decays into a $b$ quark emitting a $W$ boson as

*Talk given at the International School Seminar’97, “Structure of Particles and Nuclei and their Interactions”, (Tashkent, Oct. 6–13, 1997)
a real process and a single top decay width becomes very large, $\Gamma(t \rightarrow bW) \approx 1.5\text{GeV}$ for $m_t = 175\text{GeV}$. Therefore, the life time of the $t$ quark becomes $\approx 10^{-25}\text{sec}$ which is shorter that the hadronization time $\approx 10^{-23}\text{sec}$ and there is no possibility to make hadrons containing top quarks\[4\].

In summary, physics of the $u$, $d$ and $s$ quarks is something similar to the solid state physics. Both of them are described well by effective theories with beautiful symmetries. On the other hand, since a top quark is too heavy to make hadrons containing it, we do not need to worry about the complicated nonperturbative effect of its hadronization. One can directly test the perturbative QCD in top physics. The situation is, in some sense, similar to a gas: both of them are rather simple systems. However, physics of charm and bottom quarks is far from these two limit. It is something similar to physics of liquid which is in between solid and gas. To understand physics of charm and bottom quarks, we need knowledge of both perturbative and nonperturbative QCD. In other word, heavy quarks, i.e. charm and bottom quarks provide an important playground for testing both perturbative and nonperturbative QCD. For the nonperturbative and static region, the potential model approach is still effective in the spectroscopy of these heavy flavored hadrons in addition to the HQET\[5\]. On the other hand, the heavy quarks are produced only via gluon interactions in high energy scatterings and thus play an important role in extracting an information on perturbative QCD.

Recently, there have been new interests in physics of heavy flavored quarks: how they work effectively for extracting the information on the spin structure of nucleons and also how they are produced in high energy collisions. In this talk, I concentrate on two topics related to these subjects which we have recently studied.

2. Polarized structure functions of nucleons

Recent high energy polarized experiments have revealed a much more fruitful structure of nucleons than ever considered. One of the most serious problems is so-called the spin puzzle\[4\], i.e.

$$\frac{1}{2} = \frac{1}{2}\Delta \Sigma + \Delta g + \langle L_Z \rangle_q + \langle L_Z \rangle_g,$$

$$\Delta \Sigma = \Delta u + \Delta d + \Delta s \approx 0.3,$$

$$\Delta s \approx -0.12,$$

where $\Delta \Sigma$ and $\Delta g$ are the amount of the proton spin carried by quarks and gluons, respectively, and $\langle L_Z \rangle_q, g$ implies the orbital angular momenta of quarks and gluons. Although there have been many theoretical and experimental studies so far, many questions are still to be answered: where does the proton spin come from?, why are $s$ quarks polarized negatively?, what about gluons?, how does QCD works? and so on.

In order to go beyond the present understanding on the nucleon spin structure, it is very important to measure the polarized gluon and sea-quark distribution. Here I am interested in the gluon polarization in the proton. Although there have been many discussions on the gluon polarization, knowledge of the magnitude $\Delta g$ and the behavior $\delta g(x, Q^2)$ is still poor. Among many processes which are sensitive to $\delta g$, here we propose a different process(fig.1),
Figure 1: The lowest order QCD diagram for $\Lambda^+_c$ leptoproductions in unpolarized lepton-polarized proton scatterings.

\[
\ell + \bar{p} \rightarrow \bar{\Lambda}^+_c + X,
\]

(4)

to get further information on polarized gluons, expecting that the process can be observed in the forthcoming COMPASS experiment, where the arrow attached to particles means that these particles are polarized. The process is expected to be effective for testing $\delta g$ since its cross section is directly proportional to $\delta g$. Furthermore, the spin of $\Lambda^+_c$ is carried by the $c$ quark and thus measurement of polarization of $\Lambda^+_c$ in the target fragmentation region could determine the gluon polarization, $\delta g$.

An interesting parameter is the two-spin asymmetry,

\[
A_{LL} = \frac{d\sigma_{++} - d\sigma_{+-} + d\sigma_{-+} - d\sigma_{--}}{d\sigma_{++} + d\sigma_{+-} + d\sigma_{-+} + d\sigma_{--}} = \frac{d\Delta\sigma/dy}{d\sigma/dy},
\]

(5)

where $d\sigma_{+-}$, for instance, denotes that the spin of the target proton and produced $\Lambda^+_c$ is positive and negative, respectively. The explicit expressions of the spin-independent and spin-dependent cross sections are given in ref. [7]. Using the typical examples of polarized gluon distributions (GS95 [8], BBS95 [9], GRV95 [10]) (fig. 2), we have calculated the $A_{LL}$ at a CMS energy of the virtual photon–proton collision, $\sqrt{s} = 10\text{GeV}$ (which corresponds to $\gamma^*$ energy $\nu = 56\text{GeV}$) and a momentum transfer squared $Q^2 = 10\text{GeV}^2$ (fig. 3), whose kinematical region can be covered by COMPASS experiments. We have found that the $A_{LL}$ largely depends on the behavior of polarized gluons. Thus we can say that the process might be promising to test various models of polarized gluons.
Figure 2: The $x$-dependence of polarized gluon distributions at $Q^2=10\text{GeV}^2$. The solid, dotted, dash-dotted and dashed lines indicate the set A, C of ref.[8], ref.[9] and the ’standard scenario’ of ref.[10], respectively.

Figure 3: The spin correlation asymmetry $A_{LL}$ as a function of rapidity $y$ at $\sqrt{s}=10\text{GeV}$ and $Q^2=10\text{GeV}^2$. Various lines represent the same as in fig.2.

3. Heavy quarkonium productions

So far, the standard model is extremely successful in describing the present experimental data. However, recent observation[11] by the CDF collaboration has shown that the production cross section of charmonium at large $p_T$ region in $pp$ collisions at Tevatron are order of magnitude larger than the conventional QCD prediction by the color-singlet model. This dramatic discrepancy might make a new step toward the deep understandings of heavy quarkonium production mechanism. To remove such a big discrepancy between the experimental data and the prediction of the color–singlet model, an interesting new color–octet model has been proposed recently by several people[12]. Physics of the color–octet model whose theoretical ground has been rigorously formulated by a new effective theory called the nonrelativistic QCD(NRQCD)[13], is now one of the most interesting topics for heavy quarkonium productions at high energy. Although several processes have been already suggested for testing the model[14], the discussion seems still controvertial[15]. To go beyond the present theoretical understandings, it is necessary to study other processes. To test the model, we propose here another process,

$$\vec{p} + \vec{p} \to \psi' + X,$$

(6)

at small $p_T$ regions[16]. Since the process is dominated by the gluon-gluon fusion, there is no direct production of color-singlet $\psi'$ because of charge conjugation. There are only two states which are expected to contribute to the $\psi'$ production in the final states: the color-octet state decaying to $\psi' + g$ and the $2^3P_2$ state decaying to $\psi' + \gamma$. By using typical examples of polarized gluon distributions presented in fig.2, we have calculated the two-spin asymmetry $A_{LL}$ for the $\psi'$ produced in this process and found that it is positive for the color-octet state and negative for the $2^3P_2$ state. The spin-dependent and
spin-independent cross sections of $\psi'$ productions via the color-octet state depend on the parameters, $\langle O_8^{\psi'}(1S_0) \rangle$, $\langle O_8^{\psi'}(3S_1) \rangle$ and $\langle O_8^{\psi'}(3P_0) \rangle$ [7], which are nonperturbative long-distance factors associated with the production of a $c\bar{c}$ pair in a color-octet $1S_0$, $3S_1$ and $3P_0$ states, respectively. The model can also be applied likewise even for the $\Upsilon'$ production. These nonperturbative factors are obtained from recent analysis on charmonium and bottomonium hadroproductions:

$$\langle O_8^{\psi'}(3S_1) \rangle \approx 4.6 \times 10^{-3} \text{[GeV}^3],$$

$$\langle O_8^{\psi'}(1S_0) \rangle + \frac{7}{m_c^2} \langle O_8^{\psi'}(3P_0) \rangle \approx 5.2 \times 10^{-3} \text{[GeV}^3],$$

$$\frac{1}{5} \langle O_8^{\psi'}(1S_0) \rangle + \frac{1}{m_b^2} \langle O_8^{\psi'}(3P_0) \rangle \approx (5.9 \pm 1.9) \times 10^{-3} \text{[GeV}^3],$$

for $\psi'$ productions [13] and

$$\langle O_8^{\Upsilon'}(3S_1) \rangle \approx 4.1 \times 10^{-3} \text{[GeV}^3],$$

$$\langle O_8^{\Upsilon'}(1S_0) \rangle + \frac{7}{m_b^2} \langle O_8^{\Upsilon'}(3P_0) \rangle \approx 3.0 \times 10^{-2} \text{[GeV}^3],$$

$$\frac{1}{5} \langle O_8^{\Upsilon'}(1S_0) \rangle + \frac{1}{m_b^2} \langle O_8^{\Upsilon'}(3P_0) \rangle \approx (9.1 \pm 7.2) \times 10^{-3} \text{[GeV}^3],$$

for $\Upsilon'$ productions [18] [19]. The $A_{LL}$ via the color-octet state largely depend on the ratio, $\frac{\tilde{A}_{LL}}{\bar{A}_{LL}} \equiv \frac{\langle O_8^{\psi'}(1S_0) \rangle - \frac{1}{5} \langle O_8^{\psi'}(3P_0) \rangle}{\langle O_8^{\psi'}(1S_0) \rangle + \frac{7}{m_b^2} \langle O_8^{\psi'}(3P_0) \rangle}$, whose values range as $\frac{\tilde{A}_{LL}}{\bar{A}_{LL}} \approx 3.6 - 8.0$ for $\psi'$ productions and $\frac{\tilde{A}_{LL}}{\bar{A}_{LL}} \approx -1.88 - 8.01$ for $\Upsilon'$ productions. Those for the $2^3P_2$ state depend on the derivative of the wave function at the origin, $|R_{2^3P_2}(0)|$, whose value has been estimated by the potential models [20]: $|R_{2^3P_2}(0)| = 0.076\text{GeV}^5 - 0.186\text{GeV}^5$ for $\psi'$ and $|R_{2^3P_2}(0)| = 1.417\text{GeV}^5 - 2.067\text{GeV}^5$ for $\Upsilon'$, depending on the type of potentials. We have found that the $A_{LL}$ for the sum of contributions from the color-octet state and the $2^3P_2$ state becomes positive for the present parameter regions, in particular, at $\sqrt{s} = 50\text{GeV}$: the results with typical parameters are shown in figs.4 and 5. From this result, one can conclude that if we observe a positive $A_{LL}$ in the future RHIC experiment, we can definitely say that the color-octet model really contribute to this process. The process is therefore very effective for testing the color-octet model. Since the results largely depend on the ratio, $\frac{\tilde{A}_{LL}}{\bar{A}_{LL}}$, it is very important to determine the value from other experiments in order to give a better prediction. Furthermore, the process is effective for testing the spin-dependent gluon distribution in the proton because its cross section is directly proportional to the product of $\delta g(x)$ in both protons.

4. Outlook

The production of heavy quarks and quarkonia is a very important subject to test the standard model and QCD, and furthermore to go beyond the present understandings of particle physics. Polarized experiments are the most promising way for testing various theories on heavy quark physics with spin. In addition to the running experiments, a lot of interesting polarized experiments, such as, COMPASS experiment at CERN, RHIC project, future polarized HERA experiments, polarized $\gamma p$ experiments at SPring-8(Japan), MAMI(Germany), TJNAF(USA), and so on, are planned at many places in the
world and will come out soon. These experiments will lead us to a new stage for studying heavy quark physics with spin.

While a lot of experimental and theoretical progress has been done so far for the spin physics and heavy quark productions, heavy quark physics is still a challenging subject which needs further investigation.

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