Abstract for an Invited Paper
for the HAW09 Meeting of
The American Physical Society

Theory of Transverse Spin and Transverse Structure of the Nucleon

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Large single transverse spin asymmetries (SSA) observed in various collision processes opened a new window to disentangle QCD dynamics and quark-gluon substructure of the nucleon. Since SSA is a "naively T-odd" observable, it can only occur as an interference between the scattering amplitudes which have different complex phases in a time-reversal invariant theory like QCD. A conventional framework for hard inclusive processes, i.e. perturbative QCD in the twist-2 level, can only give rise to a negligible asymmetry and thus can not explain the observed data. Understanding the origin of the large SSAs requires the extention of the framework of the QCD hard processes, and by now QCD mechanisms leading to large SSAs have been clarified in greater detail. These mechanisms based on different perspectives introduce new concepts describing the nucleon structure not present in the conventional parton model, such as "parton's intrinsic transverse momentum" and "multi-parton correlations." Precise and unambiguous definition of these ideas requires much more careful theoretical analyses than the twist-2 case, in particular, in connection with the universality of the parton distribution/fragmentation functions, gauge invariance and factorization properties of the cross sections. In the literature, QCD mechanisms for SSAs are often classified into two categories. One is based on the (naively) "T-odd" distribution and fragmentation functions in the transverse momentum dependent (TMD) factorization approach. Sivers and Collins functions are typical examples for this one. The other one is based on the twist-3 quark-gluon (more generally, multi-parton such as triple-gluon) correlation functions in the collinear factorization approaches. The former mechanism can describe SSAs in the small-p_T region ($p_T \ll Q$) as a leading-twist effect, while the latter one describes SSAs in the large p_T region as a twist-3 effect. Both approaches have been applied to study SSAs in various processes, such as semi-inclusive deep-inelestic-scattering (SIDIS), Drell-Yan processes, $p^\uparrow p \to hX$ ($h = \pi,\ K\,D$ etc) etc, for which experimental measurements are ongoing at DESY, CERN, J-Lab and BNL-RHIC etc. Although the starting points of the analysis and the applicable kinematic region for these two mechanisms are different, they are shown to give identical SSAs in the intermediate region of p_T for the "Sivers" type SSA. Universality of the TMD functions and the factorization property with TMD functions have been studied in detail. Gauge invariance and the factorization property of the twist-3 cross section in the latter approach is also understood. In this talk, I will first review recent developments in the theoretical frameworks for SSAs described above, and then I will present our recent works on SSAs based on the twist-3 mechanisms. I will discuss the azimuthal structure of the twist-3 single-spin-dependent cross section for SIDIS and A_N for $p^\uparrow p \to hX$ including all kinds of pole contributions.