XIANGDONG JI
Professor of Physics

Education:

B.Sc.	Tongji University, Shanghai, China	1982
M.Sc.	Drexel University	1985
Ph.D.	Drexel University	1987

Experience in Higher Education:

1987	Drexel University	Postdoctoral Research Fellow
1987-1989	California Institute of Technology	Postdoctoral Research Fellow
1989-1991	Massachusetts Institute of Technology	Sponsored Research Staff
1991-1996	Massachusetts Institute of Technology	Assistant Professor
1996-1998	University of Maryland	Assistant Professor
1998-2001	University of Maryland	Associate Professor
2001-	University of Maryland	Professor
2004-	Peking University, P. R. China	ChangJiang Chair Vis. Professor of Theoretical Physics
2005-	Center for High-Energy Physics, Peking U.	Associate Director
2007-2009	Maryland Center for Fundamental Physics, University of Maryland	Director
2009-	Shanghai JiaoTong University,	ShuanQian Chair Professor (part-time)

Synergistic Activities:

Chairman, Gordon Conference on Nuclear QCD in 1999
Fellow, American Physical Society, 2000
Member, NSAC Nuclear Theory Subcommittee, 2003
Recipient of Outstanding Young Overseas Chinese Research Award, 2003-2006
Chair, APS Nuclear Division Hadronic Physics Town Meeting, Jan. 2007
Member, DOE and NSF Nuclear Science Advisory Committee, 2007-2010
Member, Executive Board of High-Energy Physics Society in China, 2011-

Recent Research

In the last year, Dr. Ji's theoretical research has been focused on two different directions: QCD physics and weakly-interacting massive particles (WIMPs) as dark matter. In QCD physics, Dr. Ji continues his work about the angular momentum study, in particular, he and his collaborators have worked on matching the full QED angular momentum operators to that in the non-relativistic effective theory when fermions are heavy. Ji and collaborators have also reconsidered the use of Wigner distribution functions in describing the properties of hadrons. They found that there is a choice of gauge link for transverse-momentum dependent distributions so that the momentum of the Wigner distribution yields the correct angular momentum sum rule. Such choice also renders this distribution calculable in lattice QCD. Finally, Ji's work on WIMP dark matter is mainly about the collider constraint. This is because recent experimental data indicated that the WIMPs are as light as 10 GeV. If so, they shall be copiously produced in a hadron collider.

A. *Effective Angular Momentum Operators in Non-relativistic Quantum Electrodynamics and Matchings at One-Loop Order*

We derive the effective angular momentum operator to $1/m^2$ and one-loop order in non-relativistic quantum electrodynamics (NRQED). In both dimensional and three-momentum-cutoff regularization schemes, we obtain the non-relativistic expansion for the spin and orbital angular momentum operators of the electron and photon, respectively. Our result is useful in precision calculations of the angular momentum properties for non-relativistic QED bound states, such as atom systems.

In recent years, effective theories including non-relativistic QED (NRQED) and the non-relativistic QCD (NRQCD) have become a usual tool in solving non-relativistic bound states. NRQED has been used to calculate the hyperfine splitting and lamb shift of the hydrogen system with considerable simplification. NRQCD has been used in analyzing the heavy quarkonium inclusive production in colliders and precision bound-state calculations on the lattice. By observing that the Coulomb interactions exchanging momentum at much lower scale compared to the fermion mass m, one can integrate out the large momentum scale, resulting in higher dimensional effective operators suppressed by powers of $\frac{p}{m} \ll 1$. In effective theories, relativistic and radiative corrections to bound state problems can be systematically expanded in terms of $\frac{p}{m}$ and $\alpha_{\rm EM}$. The non-relativistic bound state wave function properly sums up all order corrections due to the Coulomb photon exchange. Therefore, the NRQED as an effective field theory, is capable of describing the hydrogen atom up to any definite order with desired precision in a language familiar in quantum mechanics.

In the non-relativistic limit, the orbital angular momentum $\vec{L}$ and spin $\vec{S}$ of the electron are both conserved and can be used to classify the energy eigenstates. Moreover, the contribution from the gauge potential in the orbital part is proportional to the velocity and hence negligible. $\vec{L}$ is then the usual non-relativistic angular momentum. When taking into account the relativistic effects and quantum corrections, the angular momentum operator becomes more complicated. For example, for relativistic Dirac Hamiltonian, neither L nor S maintains as a good quantum due to corrections of order v^2/c^2. These are relativistic corrections starting at order $\mathcal{O}(\alpha_{\rm EM}^2)$. Radiative corrections will further contribute at order $\mathcal{O}(\alpha_{\rm EM}^3)$.

In this work, we derive the effective angular momentum operator in NRQED. For this purpose, we will construct a set of gauge-invariant effective operators in the non-relativistic theory. The matrix elements of the spin (orbital) angular momentum for the electron and the gauge fields are calculated in full QED and matched to the effective theory up to order $\frac{\alpha_{\rm EM}}{m^2}$. Using the power counting in NRQED, we have applied the one-loop matching result to calculate the angular momentum carried by radiative photons in the hydrogen atom up to $\mathcal{O}(\alpha_{\rm EM}^3)$. The further extension to the angular momentum decomposition in QCD/NRQCD will be presented elsewhere.

[1] P. Y. Chen, X. Ji, and Y. Zhang, JHEP **1102**, 107 (2011). [arXiv:1012.3668 [hep-ph]]

(P. Y. Chen, X. Ji, Y. Zhang (ICTP, Trieste))

B. *Comment on "Do Gluons Carry Half of the Nucleon Momentum?" by X. S. Chen et. al. (PRL103, 062001 (2009))*

In a recent paper by Chen et al. (PRL103, 062001 (2009)), the textbook definition of a charged-particle's momentum and angular momentum in gauge theories has been questioned. The authors claim they have found a "proper" definition, and challenge the well-known result in perturbative quantum chromodynamics (QCD) that the gluons carry one-half of the nucleon momentum in asymptotic limit. Here I argue that the textbook result stands, and the incorrect conclusion of the paper arises from a misunderstanding of gauge symmetry.

In Chen et al.'s paper, a "sound" definition of a charged particle's momentum in a U(1) gauge field A^μ is purported to be (see Eq. (6) in the paper)

$$P_q^\mu = P^\mu - qA^\mu_{\rm pure}/c \ , \tag{1}$$

where P^μ is the canonical momentum and $A^\mu_{\rm pure}$ is "a pure gauge term transforming in the same manner as does the full A^μ" and always gives "null field strength." This magical $A^\mu_{\rm pure}$ allows a "gauge-invariant" definition of P_q^μ and "physical" $A^\mu_{\rm phys} = A^\mu - A^\mu_{\rm pure}$. The authors claim that the quark's P_q^μ shall be measurable in deep-inelastic scattering (DIS) and shall contribute 1/5 of the nucleon momentum.

First of all, separating $\vec{A}$ into $\vec{A}_{\rm phys}+\vec{A}_{\rm pure}$ cannot be uniquely done by the conditions $\vec{\nabla}\cdot\vec{A}_{\rm phys} = 0$ and $\vec{\nabla}\times\vec{A}_{\rm pure} = 0$, contrary to authors' claim. In fact, one can always add/subtract a term $\vec{\nabla}\phi$ with $\nabla^2\phi = 0$ to change the separation. A simple counterexample is that of a constant magnetic field in the z-direction. $\vec{A}_1 = (By, 0, 0)$ and $\vec{A}_2 = (By, -Bx, 0)/2$ both must be "physical" according to the authors. Of course, one can add more constraints to make the separation unique. However, this amounts to defining $\vec{A}_{\rm phys}$ by gauge fixing and performing calculations under a fixed gauge.

Next, what is theoretically sound to define and experimentally measurable in electromagnetism are already well known. The kinematic momentum of a charged particle is

$$\vec{\pi} = \vec{P} - q\vec{A}/c \ , \tag{2}$$

with the full gauge field $\vec{A}$ required. It is $\vec{\pi}$ which gives rise to the kinetic energy of the particle $E = \vec{\pi}^2/2m$, and it is $\vec{\pi}$ which generates the electric current, $\vec{j} = (q/m)\vec{\pi}$. Feynman in his famous lectures provided a beautiful example (Sec. 21-3) to demonstrate that $\vec{\pi}$ is the momentum related to the velocity of a charged particle measurable experimentally. $A^\mu_{\rm phys}$ has never been considered as a meaningful observable in electromagnetism.

In the context of QCD, it is π^μ which appears in the twist-2 operators of the operator product expansion for deep-inelastic scattering (DIS). The light-cone plus(+) component of the operators generates the light-momentum of a parton in $A^+ = 0$ gauge. There is no place for P_q^μ (Eq.(1)) in any QCD experimental observables. In particular, the parton distributions advocated by the authors do not appear in any factorization of hard processes.

Finally, the textbook procedure to construct gauge-invariant quantities is dictated by Lorentz symmetry, which requires a four-vector field to describe the two degrees of freedom of a massless spin-1 particle. To ensure the gauge part does not contribute to observables, one first formulates a Lorentz-invariant and gauge symmetric theory and then imposes gauge conditions in quantization. The reverse of the procedure, namely constructing observables directly in terms of "physical" degrees of freedom after imposing the gauge conditions, does not lead to useful physics because 1) the observables generally do not have proper Lorentz transformation, 2) they generally are non-local, and 3) they generally have no physical measurements. This, unfortunately, is exactly what Chen et al.'s paper is advocating. Giving up locality and Lorentz symmetry, one can invent a myriad gauge-invariant "observables" which can never actually be observed.

[1] X. Ji, Phys. Rev. Lett. **106**, 259101 (2011).

(X. Ji)

C. Phase-Space Tomography of the Proton

The proton can be imaged in infinity momentum frame and transverse phase space (joint transverse coordinates and momentum) through quantum Wigner distributions. We discuss the physical motivation and practical tools to study such distributions, with illustrative examples. The physics program at Jefferson Lab 12 GeV upgrade and planned electron-ion collider (DIS) will be ideal to make such a study.

Exploration of the internal structure of the proton and neutron has been continuing for more than half of a century. The initial probe is elastic electron scattering which allows one to measure the static charge and current distributions. In quantum chromodynamics (QCD), this can be thought of as measuring the spatial distributions of the quarks. With the advent of deep-inelastic scattering (DIS), one can probe the quark longitudinal momentum distributions: counting the number of quarks with momentum $x\vec{P}$, where the nucleon momentum $\vec{P}$ is asymptotically large (infinite momentum frame or IMF). IMF is a good frame of reference to depict the nucleon structure because, according to Feynman, the interactions between the constituents are slowed down infinitely, and they appear to be quasi-free. In such a frame, the spatial distributions of the quarks appear in the transverse direction, or the impact parameter space ($\vec{b}_\perp$).

About fifteen years ago, generalized parton distributions (GPD's) were realized as a novel experimental probe for joint distributions in longitudinal momentum x and transverse coordinate $\vec{b}_\perp$. This distribution makes the probability sense because momentum and coordinates are in different dimensions. Experimental programs were proposed to measure the GPD's and lattice calculations have also been made. An exciting program at Jefferson Lab 12 GeV upgrade is available. A related effort has gained a lot of attention, namely measuring the transverse-momentum dependent parton distributions (TMD's). These are a class of joint distributions in longitudinal momentum x and transverse-momentum $\vec{k}_\perp$. Many experiments have also been designed to measure these quantities as well. One might suspect that these distributions must be similar because the coordinate and momentum space wave functions must be related by Fourier transformation. In reality, however, GPD's and TMD's are very different observables because the nucleon is a many-body system. Even in QCD theory, they have very different status.

A more dynamical picture of a system often exhibits in the phase space, namely, through joint distributions in conjugating momentum and coordinate spaces. In quantum systems, this is made possible through the Wigner distributions, a classical analogue of phase-space distribution in statistical mechanics. Wigner distributions were considered as a theoretical construct rather than an experimental observable. With the advent of novel experimental technology, Wigner distributions have been measured routinely now in many quantum systems. For the nucleon structure, a general Wigner distribution was first introduced by Belitsky, Ji and Yuan. However, being too general and without obvious experimental measurements, the concept is of limited use. In this work, we argue that a version of the Wigner distribution with joint coordinate and momentum information ($b_\perp$, $k_\perp$) can be introduced and studied. The result will provide a rich transverse phase-space tomography of the nucleon.

[1] X. Ji, X. Xiong (Peking U.), and F. Yuan, to be published.

(X. Ji, X. Xiong, F. Yuan (LBNL)

D. Collider Constraint on Low-Mass Dark Matter Particles

Light WIMP-like signals were reported by dark matter direct detection experiments, and dark matter candidates in this energy range can be constrained by collider experiments. Furthermore, the thermal annihilation pattern of dark matter with mass around 10 GeV is different from weak scale dark matter. For new mediators apart from Z boson and Standard Model Higgs, in a generic case, the interaction between the mediator and Standard Model particles suffer from stringent constraint from flavor changing neutral current. In this work, the constraints on scalar mediator and vector mediator with scalar and spin-1/2 spinor dark matter cases are considered. We show that the parameter space of around 10 GeV dark matter is strongly constrained.

The identity of the Cold Dark Matter (CDM) in the universe is one of the outstanding mysteries. In the past couple of decades, much effort has been devoted to the modeling and detection of WIMP dark matter with mass in the range of 100s GeV to 1 TeV. More recently, a scenario with lighter dark matter, 10 GeV, has been put forward as a possible alternative. In all of these scenarios, dark matter has non-vanishing couplings to the SM particles. Experiments designed to observe dark matter through these interactions are crucial in probing the properties of the dark matter. One such promising approach is the direct detection. The current direct detection of dark matter can be roughly classified into two frontiers. The first frontier is for dark matter mass in the range of 100s GeV 1 TeV, where the constraint on the spin-independent dark matter nucleon cross section is around 10^{-44} to 10^{-45} cm^2. Along this frontier, the direct searches are starting to set interesting constraints on the "conventional" WIMP candidate, such as the LSP dark matter of supersymmetry. The second frontier is in the regime of light, 10 GeV, dark matter. If the dark matter particles are indeed light, they shall be copiously produced in the LHC and Tevatron colliders. In this work, we use a Z' model to study the constraint of light dark matter particles. The result shows that the collider search is competitive with the current direct dark matter detection. A paper on this will be published soon.

[1] H. P. An, X. Ji and L. T. Wang, to be published.

(H. P. An, X. Ji, L. T. Wang (U. Chicago))