# A Brief Introduction to the Proton Spin Puzzle

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### Section 1: Introduction

Over the past summer and throughout this semester I have had the opportunity to work on a particle physics research project. My project concerns the validity of TMD factorization in the Semi-Inclusive deep inelastic scattering (SIDIS) at CLAS12, a detector at Jefferson Lab. Specifically, I have worked on calculating SIDIS kinematics from CLAS12 data (and simulation) that can be used to calculate a quantity called affinity that estimates how well certain factorization schemes describe the QCD physics occuring in SIDIS. My project is tiny part of the giant global effort to describe the dynamics and structure of nucleons: the proton and neutron. This effort was jump started in 1988 when the European Muon Collaboration published the first results of , a quantity that describes how much of the proton's spin is made up from valence quark spin. The simplest quark model of the proton describes the nucleon as a collection of three quarks bound together by nuclear gluon, where the proton's 1/2 spin is the sum of the spins of the 1/2 spin quarks. SIDIS experiments have forced physicists to create more complex nucleon models where the three valence quarks orbit through a sea of quark-antiquark pairs. The proton spin can thus originate in parts from valence quark spin and angular momentum, sea quark spin and angular momentum, and even gluon spin and angular momentum. This paper aims to introduce the experiments that began and continued these efforts in proton spin studies, explain the impact of SIDIS studies on the field, and connect the physics back to the basics of spin taught in Modern Physics courses

First the paper will provide an overview of spin for elementary particles and how the quantity can be used to describe (word for not elementary) particles. I will then discuss the Bjorken and Ellis-Jaffe sum rules and their relevence to nucleon spin, as well as the experiments that tested their validity. These experiments lead into the current advances concerning the proton spin puzzle where the paper concludes.

### Section 2: What is spin? From electrons to protons

Before the discovery of electron spin, physicists knew about the orbital angular momentum of the electron that results from it's orbits around the nucleus. Furthermore, the introduction of quantum mechanics brought on new experiments to verify the quantization of electron angular momentum. Perhaps the most famous experiment on the matter was thought up by Otto Stern and performed by Walther Gerlach, and has since been referred to as the Stern-Gerlach experiment. In this experiment, a beam of silver atoms are sent through a non-uniform magnetic field and deposited onto a glass plate for observation. The physicists used a non-uniform field to exert a force on any particle with magnetic moment. This deflection depends on the alignment of the particle's magnetic moment, and thus the physicists intended to show the quantization of space due to discrete levels of alignment creating discrete collections on the observation plate. Under the assumption that the electron's magnetic moment depends solely on the orbital angular momentum, they expected to see deposits on the plate. From a classical perspective, there would be no constraint on the number of deposits as the angular momentum is not quantized in classical physics, and thus the experiment was created as an attempt to show space quantization. However, the result did not follow either theory, and instead two distinct components showed on the plate. Furthermore, the silver atoms used in the experiment had no angular momentum in their ground state where the valence electron resides, corresponding to . The present theory of quantized orbital angular momentum had no explanation for the two components, suggesting the electron may have another contribution to its magnetic moment (\_\_Physics textbook citation).

T. E. Phipps and J. B. Taylor performed the Stern-Gerlach experiment in 1927, this time using hydrogen atoms to remove any sources of uncertainty in using a complex silver atom. The physicists' data showed the same result as the original experiment, confirming that there was another source of the electron's magnetic moment. Graduate students at the University of Lieden developed a theory to explain the phenomena and described the magnetic moment as a result of the electron spinning on its axis. Although they were incorrect about the electron spinning, the name stuck and a theory of spin angular momentum was created. The students conjectured that the moment obeyed the same space quantization rules as orbital angular momentum, producing a formula for the number of components of spin angular momentum for a particle: . In both the previously mentioned experiments, the results showed two discrete components which indicates the value for the spin quantum number: . Furthermore, they gave formulas for the z-component and magnitude of spin angular momentum:

$$S\_z = m\_s \hbar \\
\nonumber|S\nonumber| = \sqrt{s(s+1)\hbar} = \frac{\sqrt{3}}{2} \hbar\qquad\text{(1)}$$

Here, . Because the magnitude of the spin angular momentum depends only only constants, the spin magnetic moment must be an intrinsic property of the electron.