CHAPTER 1

INTRODUCTION

1.1 Search for Understanding

At some very basic level, physicists are driven by the desire to understand the world around them. We perform experiments and invent theories that probe and describe how things work. Good experiments are sometimes described as "beautiful" and simple theories are sometimes called "elegant." It seems as if there is an underlying desire to have nature, its behavior, and descriptions of its behavior be beautiful, elegant, and simple.

When formulating theories one would like things to be symmetric in some way, just like nature. For example, the physics of a particle in motion is the same regardless of whether time is running forward or backward. Indeed, symmetries are so fundamental that the definite relationship between invariance or symmetry properties of a system and its conserved quantities is described in the mathematical Noether's Theorem [1]. So, when a symmetry is broken, physicists take notice.

Such was the case when parity nonconservation (PNC) was first observed in nuclear beta decay by Wu and collaborators [2]. In this experiment, the scientists studied the decay ${}^{27}\mathrm{Co}^{60} \rightarrow^{28} \mathrm{Ni}^{60} + e + \bar{\nu}$ by measuring the direction of the emitted electrons relative to the magnetic moment of the ${}^{27}\mathrm{Co}^{60}$ nuclei. They found that the direction of emission was not symmetric with respect to the plane perpendicular to the magnetic moment. Instead, there is a preferred direction of emission that is "left-handed" with respect to the direction of an imaginary current that would produce the same magnetic moment of the $^{27}\mathrm{Co}^{60}$ nucleus. The physics of the mirror image (a parity reversal) of this reaction is not the same, as shown in Fig. 1.1. In the mirror image, the electron emission is right handed. Thus, the decay does not conserve parity.

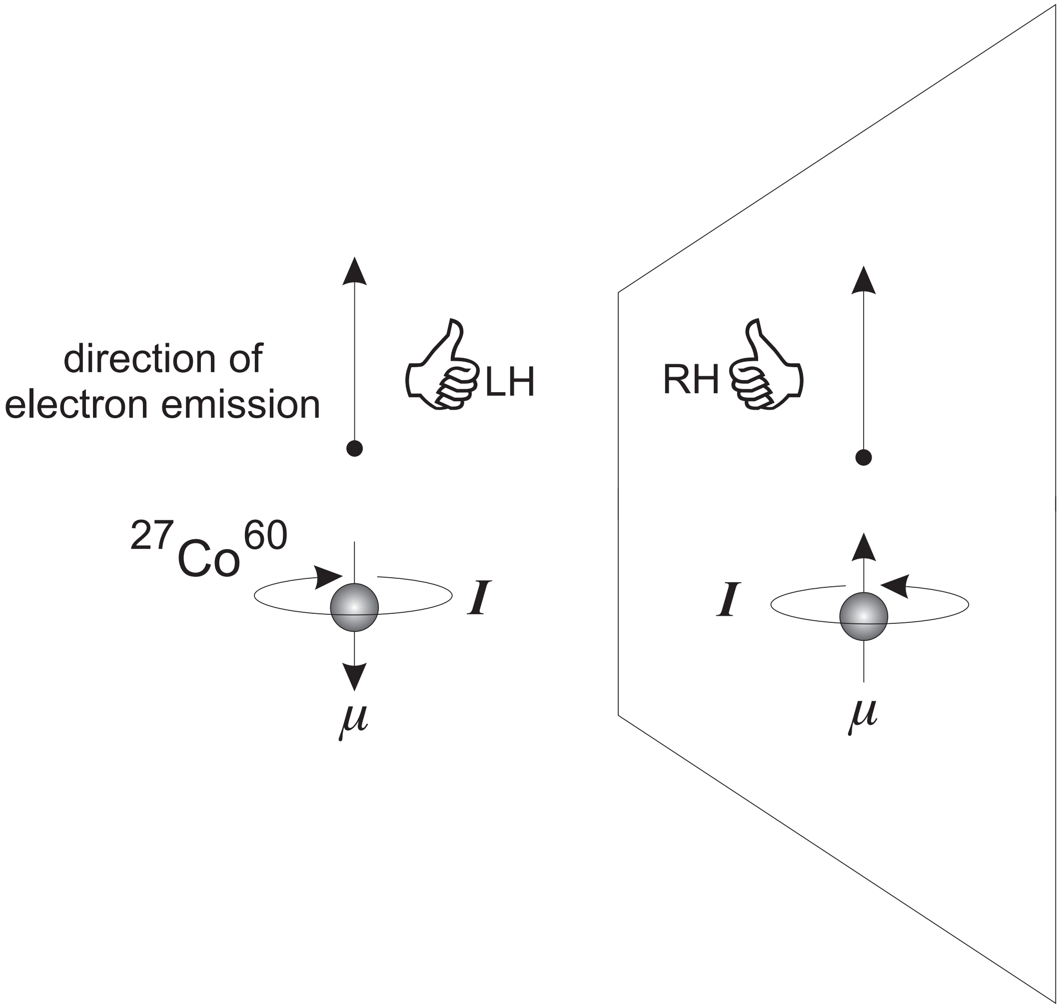

Figure 1.1: A picture of beta decay in the $^{27}\mathrm{Co}^{60}$ nucleus. Electrons are emitted in a preferred direction opposite the magnetic moment of the nucleus. In a parity reversal, the direction of the magnetic moment changes, but the direction of electron emission does not. Thus, beta decay process does not conserve parity.

1.2 The Standard Model

The force that is responsible for beta decay is the weak force, which has been unified with the electromagnetic force by a theory developed by Glashow [3], Salam [4], and Weinberg [5] in the 1960's. The Glashow-Salam-Weinberg model unifies the two forces into the electroweak force and, when combined with quantum chromodynamics, is known as the standard model. Part of this model describes the electroweak interaction between six quarks (the up, down, strange, charm, bottom, and top quarks) and six leptons (the electron, muon, tauon, and their three neutrinos). The electroweak force is mediated by four particles: the neutral photon and Z^0 boson, and the charged $W^{\pm}$ bosons.

Although the standard model predicts the electroweak interactions between particles, it is silent as to the masses of those particles. There are also three additional parameters, the fine-structure constant, α, the Fermi constant G_F, and the Weinberg angle, θ_W, whose values must be determined from experiment. In addition, the mechanism for the quarks and leptons to acquire mass is the so-called Higgs mechanism, which is mediated by the Higgs boson. The Higgs boson has never been seen, and the Higgs mechanism is poorly understood.

For the above reasons, physicists have been devoting massive amounts of time and effort to test the standard model. The high energy physics community has achieved great success in their experiments [6] (although the funding for the Superconducting Super Collider, which may have found the Higgs boson, was terminated), and many in the atomic physics community have devoted their efforts to understanding PNC in atoms to test the standard model, as suggested by Bouchiat and Bouchiat [7, 8]. Both communities' experiments have now reached the level of precision where they can test the radiative corrections and search for new physics beyond the standard model.

1.3 Parity Nonconservation in Atoms

Parity nonconservation in atoms comes from the the exchange of a Z^0 boson between an electron and a quark inside the nucleus. This interaction is to the weak force as the exchange of a photon between an electron and a proton is to the electromagnetic force. Feynman diagrams comparing these two interactions are shown in Fig. 1.2. The exchange of a Z^0 boson gives rise to a Hamiltonian that is proportional to the Dirac matrix γ^5 and the weak charge Q_W. The weak charge is a neutral analog to the electric charge e, and wherever there is an electromagnetic interaction via the exchange of a photon there is also a neutral weak interaction. In atoms, the neutral weak interaction mixes eigenstates with opposite parity, and thus provides a mechanism for electric dipole transitions that do not conserve parity. Experiments that measure the PNC electric dipole transition give access to the value of Q_W, which can then be compared to the standard model prediction.

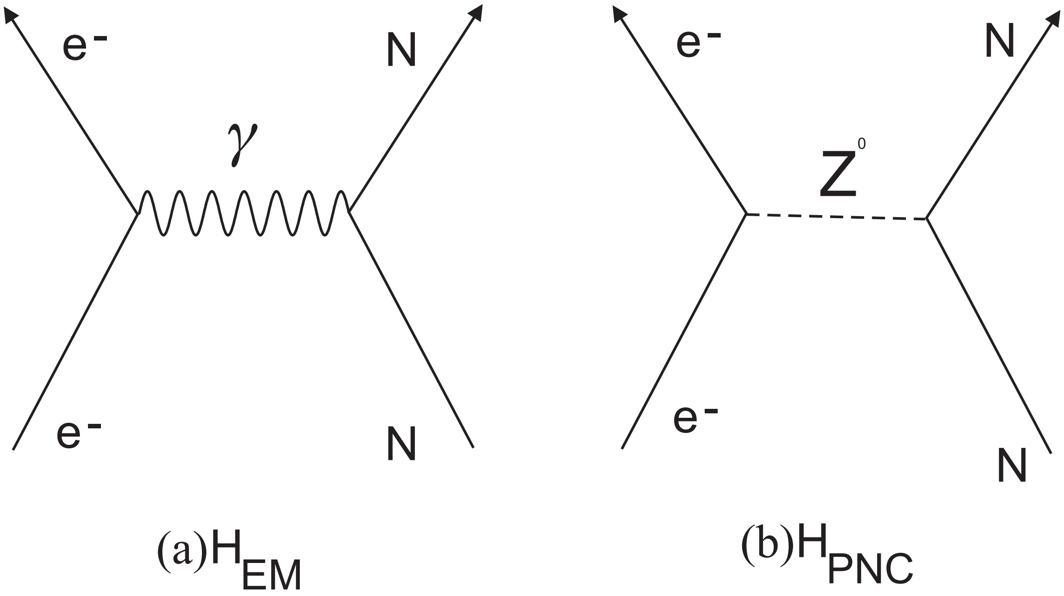

Figure 1.2: Two Feynman diagrams showing (a) electromagnetic interaction via an exchange of a photon and (b) the weak interaction via the exchange of a Z^0 boson. Here N is a nucleon.

There are two types of experiments that are typically used to measure the effect of PNC mixing: optical rotation experiments and Stark interference experiments. In optical rotation experiments [9, 10, 11, 12], linear laser light is directed through an atomic vapor. The PNC mixing induces birefringence in the vapor, and causes a rotation of the polarization of the incident light. The angle of rotation is measured and can be used to determine Q_W. Stark interference experiments measure the interference between the small PNC-induced amplitude and a larger electric-field induced electric dipole amplitude.

1.4 Parity Nonconservation Interference Measurements in Cesium

The most precise atomic PNC measurement to date [13] measures the interference between the PNC amplitude and the Stark-induced amplitude between the $6S$ and $7S$ states of cesium. The PNC amplitude is given by

$$E_{\mathrm{PNC}} \equiv \overline{\langle 7S \mid} \vec{D} \overline{\mid 6S \rangle} = (\frac{Q_W}{N}) k_{\mathrm{PNC}}, \tag{1.1}$$

where the bars over the bra and the ket indicate that they have small amounts of opposite parity states mixed into the pure parity eigenstates. Here, e is the electron charge, a_0 is the Bohr radius, N is the number of neutrons in the atom, and k_{PNC} is the value of a combination of the relevant parity conserving and PNC matrix elements. It is calculated using the *ab initio* theory of Blundell *et al.* [14] and of Dzuba *et al.* [15]. The quantity measured in Ref. [13] is the ratio of two amplitudes, $\mathrm{Im}(E_{\mathrm{PNC}})/\beta$, where β is the tensor transition polarizability that characterizes the strength of the Stark-induced transition. The test of the standard model is through the equation

$$\frac{\mathrm{Im}(E_{\mathrm{PNC}})}{\beta} = -i \frac{Q_W}{\beta N} k_{\mathrm{PNC}}. \tag{1.2}$$

This equation contains the motivation for all of the work presented in this thesis.

1.5 Motivation for the Present Work

Equation (1.2) connects the measurement of $\mathrm{Im}(E_{\mathrm{PNC}})/\beta$ and the calculation k_{PNC}, allowing the extraction of Q_W. This is atomic physics' link to the standard model.

The left side of the equation is the 0.35% measurement of Ref. [13]. The amplitude E_{PNC} is too small to measure by itself, so the experiment measures it relative to β. The right side contains Q_W, which is the quantity we wish to know, but it also contains two other parameters needed to interpret the experiment: k_{PNC} and β.

The constant k_{PNC} contains matrix elements of the Dirac matrix γ^5 that can only be calculated. Therefore, prior to this work, the uncertainty of k_{PNC} was limited by the 1% uncertainty in the atomic theory calculations. Further, while β has been determined semi-empirically, the best value was again from a 1% atomic theory calculation [14].

Because the goal of PNC measurements in cesium is a high-precision test of the standard model, as a first objective we would like to reduce the uncertainty due to the calculations. The work presented in this thesis achieves this objective.

The main stumbling block in the way of reducing the uncertainty in k_{PNC} is a 2% difference between the measurement and the calculation of the dc Stark shift of the $6S \rightarrow 7S$ transition in cesium. Because the level of agreement between experiment and theory is one indicator of the accuracy of the theory, this difference was of great concern and prevented a reduction in the uncertainty below 1%. In order to resolve this problem, we have measured the dc Stark shift, and our new measurement agrees with the predictions to 0.3%.

Our previous result for Q_W [13] used the calculated value of β from Ref. [14]. We have performed a new measurement that allows the determination of β to 0.3%, which can then be used instead of the calculation. This reduces the number of quantities that need to be calculated to determine Q_W from two to one. In addition, our result for β can be used as an additional test of the atomic theory.

This thesis is arranged as follows. Chapters 2 and 3 discuss the theory and apparatus used in the experiments described in subsequent chapters, Chapter 4 discusses the measurement of the dc Stark shift, Chapter 5 covers the determination of β, and Chapter 6 discusses the implications of the two experiments on tests of the standard model. Finally, Chapter 7 discusses the possibility of additional improvements or new measurements that may be useful for future tests of the standard model.