

---

# THESIS

---

A PREPRINT

Andrew Steinmetz \*

Department of Physics, The University of Arizona, Tucson, AZ 85721, USA

July 6, 2023

## ABSTRACT

tbw

**Keywords** relativistic mechanics · quantum mechanics · magnetic moment · magnetism

---

\*Correspondence: [ajsteinmetz@arizona.edu](mailto:ajsteinmetz@arizona.edu)

# **Chapter 1**

## **Overview and concepts**

### **1.1 Notation**

### **1.2 Spin**

#### **1.2.1 Classical spin**

#### **1.2.2 Quantum spin**

### **1.3 Magnetic and electric dipoles**

#### **1.3.1 Anomalous magnetic moment**

### **1.4 Cosmology**

#### **1.4.1 FLRW metric**

#### **1.4.2 Conserved quantities under expansion**

## **Chapter 2**

# **Classical magnetic dipole moments**

### **2.1 Stern-Gerlach force**

#### **2.1.1 Amperian and Gilbert dipoles**

### **2.2 TBMT equations**

### **2.3 Magnetic spin potential**

#### **2.3.1 Modified TBMT equations**

#### **2.3.2 Unified Amperian and Gilbert dipoles**

#### **2.3.3 Dynamic particle motion**

**Charged particles**

**Neutral particles**

### **2.4 Spin in 5D Kaluza-Klein model**

#### **2.4.1 Correspondence to particle Lagrangians**

## **Chapter 3**

# **Quantum magnetic dipole moments**

### **3.1 Schrodinger-Pauli equation**

### **3.2 Dirac and Dirac-Pauli equations**

#### **3.2.1 Ehrenfest theorem for Stern-Gerlach forces**

### **3.3 Klein-Gordon-Pauli equation**

#### **3.3.1 KGP in homogeneous fields**

#### **3.3.2 KGP for hydrogen-like atoms**

**Critical field strengths**

#### **3.3.3 Improvements to KGP**

### **3.4 Extensions to Non-Abelian fields**

## **Chapter 4**

# **Magnetization in primordial cosmology**

### **4.1 Electron-positron epoch of the universe**

#### **4.1.1 Baryon content**

Entropy conservation

#### **4.1.2 Chemical fugacity**

#### **4.1.3 Spin fugacity**

Non-relativistic spin fugacity

### **4.2 Magnetized partition function**

#### **4.2.1 Magnetized chemical potential**

#### **4.2.2 Magnetization of the medium**

### **4.3 Temperature and density effects**

## **Chapter 5**

# **Neutrinos and magnetism**

### **5.1 Neutrino masses**

#### **5.1.1 Mass hierarchy**

#### **5.1.2 Dirac neutrinos**

#### **5.1.3 Majorana neutrinos**

#### **See-saw mechanism**

### **5.2 Neutrino magnetic moments**

#### **5.2.1 Direct moments**

#### **5.2.2 Transition moments**

### **5.3 Flavor rotation**

#### **5.3.1 PMNS matrix**

#### **5.3.2 Magnetically induced rotation**

### **5.4 CP violation**

#### **5.4.1 Jarlskog invariant**