

Abstract

**Measurement of the positive kaon-argon total
hadronic differential cross section in the LArIAT
experiment**

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Abstract goes here. Limit 750 words.

Measurement of the positive kaon-argon
total hadronic differential cross section in
the LArIAT experiment

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of
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A lot of people are awesome. But not you, who are reading my thesis before it's done.

Chapter 1

Introduction

1.1 The Standard Model

The Standard Model (SM) of particle physics is the most accurate theoretical description of the subatomic world and, more generically, one of the most precisely tested theories in the history of physics. The SM describes the strong, electromagnetic and weak interactions among elementary particles in the framework of quantum field theory, accounting for the unification of electromagnetic and weak interactions for energies above the vacuum expectation value of the Higgs field. The SM does not describe gravity or general relativity.

The Standard Model is a gauge theory based on the local group of symmetry

$$G_{SM} = SU(3)_C \otimes SU(2)_T \otimes U(1)_Y \quad (1.1)$$

where the subscripts indicate the conserved charges: the strong charge, or color C, the weak isospin T (or rather its third component T_3) and the hypercharge Y. These quantities can be related to the electric charge Q through the Gell-Mann-Nishijima relation:

$$Q = \frac{Y}{2} + T_3. \quad (1.2)$$

Generation	I	II	III	T	Y	Q
Leptons	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$\begin{matrix} 1/2 \\ -1/2 \end{matrix}$	$\begin{matrix} -1 \\ -1 \end{matrix}$	$\begin{matrix} 0 \\ -1 \end{matrix}$
	e_R	μ_R	τ_R	0	-2	1
Quarks	$\begin{pmatrix} u \\ d' \end{pmatrix}_L$	$\begin{pmatrix} c \\ s' \end{pmatrix}_L$	$\begin{pmatrix} t \\ b' \end{pmatrix}_L$	$\begin{matrix} 1/2 \\ -1/2 \end{matrix}$	$\begin{matrix} 1/3 \\ 1/3 \end{matrix}$	$\begin{matrix} 2/3 \\ -1/3 \end{matrix}$
	u_R	c_R	t_R	0	$4/3$	$2/3$
	d'_R	s'_R	b'_R	0	$-2/3$	$-1/3$

Table 1.1: SM elementary fermions. The subscripts L and R indicate respectively the negative helicity (left-handed) and the positive helicity (right-handed).

In the quantum field framework, the elementary particles correspond to the irreducible representations of the G_{SM} symmetry group. In particular, the particles are divided in two categories, fermions and bosons, according to their spin-statistics. Described by the Fermi-Dirac statistics, Fermions have half-integer spin and are sometimes called “matter-particles”. Bosons or “force carriers” have integer spin, follow the Bose-Einstein statistics and mediate the interaction between fermions. The fundamental fermions and their quantum numbers are listed in Tab 1.1.

Quarks can interact via all three the fundamental forces; they are triplets of $SU(3)_C$, that is they can exist in three different colors: $C = R, G, B$. If one chooses a base where u , c and t quarks are simultaneously eigenstates of both the strong and the weak interactions, the remaining eigenstates are usually written as d , s and b for the strong interaction and d' , s' and b' for the weak interaction, because the latter ones are the result of a Cabibbo rotation on the first ones. Charged leptons interact via the weak and the electromagnetic forces, while neutrinos only interact via the weak force. The gauge group univocally determines the number of gauge bosons that carry the interaction; the gauge bosons correspond to the generators of

the group: eight gluons (g) for the strong interaction, one photon (γ) and three bosons (W^\pm, Z^0) for the electroweak interaction. A gauge theory by itself can not provide a description of massive particles, but it is experimentally well known that most of the elementary particles have non-zero masses. The introduction of massive fields in the Standard Model lagrangian would make the theory non-renormalizable, and - so far - mathematically impossible to handle. This problem is solved in the Standard Model by the introduction of a scalar iso-doublet $\Phi(x)$, the Higgs field, which gives mass to W^\pm and Z^0 gauge bosons through the electroweak symmetry breaking and to the fermions through Yukawa coupling [1,2].

1.2 Neutrinos in the Standard Model

The neutrino was introduced in the SM as a left-handed massless Weyl spinor. The Dirac equation of motion

$$(i\gamma^\mu\partial_\mu - m)\psi = 0 \quad (1.3)$$

for a fermionic field

$$\psi = \psi_L + \psi_R \quad (1.4)$$

is equivalent to the equations

$$i\gamma^\mu\partial_\mu\psi_L = m\psi_R \quad (1.5)$$

$$i\gamma^\mu\partial_\mu\psi_R = m\psi_L \quad (1.6)$$

for the chiral fields ψ_R and ψ_L , whose evolution in space and time is coupled through the mass m . If the fermion is massless, the chiral fields decouple and the fermion can be described by a single Weyl spinor with two independent components. Pauli initially rejected the description of a physical particle through a single Weyl spinor because of its implication of parity violation. In fact, since the spatial inversion operator throws $\psi_R \leftrightarrow \psi_L$, parity is conserved only if the both the chiral components

exist at the same time. **ADD CITATIONS**. For the neutrino introduction in the SM, experiments came in help of the theoretical description: the constraint of parity conservation weakened after Wu's experiment **ADD CITATIONS AND DATES**, there was no experimental indication for massive neutrinos and neutrinos likely interacted only via the left-handed component.

The symmetry group $SU(2)_T \otimes U(1)_Y$ is the only group relevant for neutrino interactions. The SM electroweak lagrangian is the most general renormalizable lagrangian invariant under the local symmetry group $SU(2)_T \otimes U(1)_Y$. The lagrangian couples the weak isotopic spin doublets and singlets described in 1.1 with the gauge bosons A_a^μ ($a = 1, 2, 3$) and B^μ , and Higgs doublet $\Phi(x)$:

$$\begin{aligned}
\mathcal{L} = & i \sum_{\alpha=e,\mu,\tau} \bar{L}'_{\alpha L} \not{D} L'_{\alpha L} + i \sum_{\alpha=1,2,3} \bar{Q}'_{\alpha L} \not{D} Q'_{\alpha L} \\
& + i \sum_{\alpha=e,\mu,\tau} \bar{l}'_{\alpha R} \not{D} l'_{\alpha R} + i \sum_{\alpha=d,s,b} \bar{q}'^D_{\alpha R} \not{D} q'^D_{\alpha R} + i \sum_{\alpha=u,c,t} \bar{q}'^U_{\alpha R} \not{D} q'^U_{\alpha R} \\
& - \frac{1}{4} A_{\mu\nu} A^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} \\
& + (D_\rho \Phi)^\dagger (D^\rho \Phi) - \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2 \\
& - \sum_{\alpha,\beta=e,\mu,\tau} \left(Y_{\alpha\beta}^n \bar{L}'_{\alpha L} \Phi l'_{\beta R} + Y_{\alpha\beta}^{n*} \bar{l}'_{\beta R} \Phi^\dagger L'_{\alpha L} \right) \\
& - \sum_{\alpha=1,2,3} \sum_{\beta=d,s,b} \left(Y_{\alpha\beta}'^D \bar{Q}'_{\alpha L} \Phi q'^D_{\beta R} + Y_{\alpha\beta}'^{D*} \bar{q}'^D_{\beta R} \Phi^\dagger Q'_{\alpha L} \right) \\
& - \sum_{\alpha=1,2,3} \sum_{\beta=u,c,t} \left(Y_{\alpha\beta}'^U \bar{Q}'_{\alpha L} \tilde{\Phi} q'^U_{\beta R} + Y_{\alpha\beta}'^{U*} \bar{q}'^U_{\beta R} \tilde{\Phi}^\dagger Q'_{\alpha L} \right). \tag{1.7}
\end{aligned}$$

The first two lines of the lagrangian summarize the kinetic terms for the fermionic fields and their coupling to the gauge bosons $A_a^{\mu\nu}$, $B^{\mu\nu}$ ¹. The third line describes the kinetic terms and the self-coupling terms of the gauge bosons. The forth line is the Higgs lagrangian, which results in the spontaneous symmetry breaking. The last

1. In gauge theories the ordinary derivative ∂_μ is substituted with the covariant derivative D_μ . Here $D_\mu = \partial_\mu + ig A_\mu \cdot I + ig' B_\mu \frac{Y}{2}$, where I and Y are the $SU(2)_L$ and $U(1)_Y$ generators, respectively.

three lines describe the Yukawa coupling between fermions and the Higgs field, origin of the fermion's mass.

The coupling between left-handed and right-handed field generates the mass term for fermions. The SM assumes only left-handed components for neutrinos, thus implying zero neutrino mass. Since any linear combination of massless fields results in a massless field, the flavor eigenstates are identical to the mass eigenstates in the SM.

1.3 Beyond the Standard Model

The discovery of neutrino oscillation and its implication of non-zero neutrino mass marks the beginning of a new, exciting era in neutrino physics: the era of physics Beyond the Standard Model (BSM) in the neutrino sector. We are currently searching for new, deeper theories that can accommodate neutrinos with non-zero mass, while remaining consistent with the rest of the Standard Model.

1.3.1 Neutrino Oscillations

1.3.2 Proton Decay

Chapter 2

Liquid Argon Detectors at the Intensity Frontier

Following the recommendation of the latest Particle Physics Project Prioritization Panel [3], the US is dedicating substantial resources to the development of a short- and long- baseline neutrino program to address the fundamental questions in neutrino physics today. A large portion of this program pivots on the Liquid Argon Time Projection Chamber (LArTPC) detector technology. In the next few years, LArTPC experiments – such as the Short-Baseline Neutrino program (SBN) and DUNE – will be major players in the intensity frontier field.

2.1 The SBN Program

2.1.1 SBN Goals

2.1.2 Neutrino Interactions and Detection

2.2 DUNE

2.2.1 DUNE Non-Accelerator Physics Program

2.2.2 Rare Decay Searches: Experimental Limit

2.2.3 Nucleon Decay Detection in LAr

2.3 Liquid Argon Time Projection Chambers at the Intensity Frontier

2.3.1 Time Projection Chamber

2.3.2 Ionization Detectors with Noble Liquids

2.3.3 LArTPC: Principles of Operation

2.3.4 Liquid Argon Ionization Charge Detection

Electron Life Time & purity

Space Charge Effect

Recombination Effect

2.3.5 Liquid Argon scintillation Light Detection

LAr Scintillation Process

Wavelength Shifting of LAr Scintillation Light

Chapter 3

LArIAT: Liquid Argon In A Testbeam

3.1 LArIAT & the Intensity Frontier

3.2 Testbeam and Beamline Detectors

3.3 In the Cryostat

3.3.1 TPC: Charge Collection

3.3.2 TPC: Light Collection System

3.3.3 Cryogenics and Purity Control

3.3.4 TPC: Electric Field Measurement

3.4 Trigger and DAQ

3.5 Control Systems

Chapter 4

Kaon Interactions in Argon

Your first chapter is probably an introduction. But who knows.

Chapter 5

Data Collection

Your first chapter is probably an introduction. But who knows.

Chapter 6

LArIAT Monte Carlo

6.1 Beamline

6.1.1 G4Beamline

6.1.2 Data Driven MC

6.2 TPC MC

Chapter 7

Energy Calibration

Your first chapter is probably an introduction. But who knows.

Chapter 8

Tracking Optimization

Your first chapter is probably an introduction. But who knows.

Chapter 9

Kaon Cross Section Measurement

Your first chapter is probably an introduction. But who knows.

Appendix A

Measurement of LArIAT Electric Field

Appendix B

Construction of A Cosmic Ray

Tagger for MicroBooNE

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