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Analysis of the $\gamma p \rightarrow \pi^+ n$ reaction for π^+ candidate events

A Thesis in
Physics
by
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Abstract

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One of the unsolved problems in nuclear physics is describing the properties of nucleons in terms of the framework provided by Quantum Chromodynamics (QCD). To do this, the comparison of experimental measurement with theoretical predictions can be made for those reactions where both theory and experiment can be performed accurately. One reaction where this is possible is pion photoproduction near threshold, which is a fundamental reaction in which a photon interacts with a a proton or neutron to produce a pion. Theoretical approaches such as Chiral Perturbation Theory and model-independent partial-wave analysis can provide accurate predictions for this reaction. A program to measure the $\gamma p \rightarrow \pi^+ n$ reaction is underway using the MAX-lab photon tagging facility in Lund, Sweden. One difficulty with these measurements is isolating the pion events from the large proton and electron background present in the counters. By searching for the extra energy deposited from the $\pi^+ \rightarrow \mu$ decay, it is possible to reliably identify the pion events. This event identification technique will be discussed and additional tests used to confirm the reliability of this method will be shown.

Dedication

This research is dedicated to Dr. O'Rielly, Dr. Fissum, Dr. Briscoe, and the entire IRES program. The experience of visiting Sweden while furthering my physics education was an amazing experience I will never forget. I would also like to dedicate this work to the University of Massachusetts Dartmouth department of Physics. My experience at UMass Dartmouth has shaped me as an academic and a person. Finally I dedicate this research to my family for continuing to challenge me to be the best I can be.

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Now, my own suspicion is that the universe is not only queerer than we suppose, but queerer than we can suppose. I have read and heard many attempts at a systematic account of it, from materialism and theosophy to the Christian system or that of Kant, and I have always felt that they were much too simple. I suspect that there are more things in heaven and earth that are dreamed of, or can be dreamed of, in any philosophy. That is the reason why I have no philosophy myself, and must be my excuse for dreaming.

J. B. S. Haldane

Chapter 1

Introduction

1.1 IRES

The International Research Experience for Students is a National Science Foundation Office of International Science and Engineering grant to promote international experiences for students while giving them an opportunity to begin researching. This particular IRES grant was to support students researching at MAX-lab in Lund, Sweden. MAX-lab is a Swedish national laboratory which contains three synchrotron particle accelerators and a photon tagging facility which makes it ideal for nuclear physics experiments involving tagged high-energy photons.

Figure 1.1: IRES participants on one of Copenhagen's many bridges.

In the summer of 2010 Dr. Grant V. O'Rielly of the University of Massachusetts Dartmouth, and Dr. William J. Briscoe of The George Washington University selected five undergraduate students to run the data acquisition system of the pion photoproduction experiment at MAX-lab. Figure 1.1 is an picture of the 2010 IRES participants in Copenhagen during a vacation day. A major part of this experience was the cultural experience, student were encouraged to explore the city and experience Swedish culture first hand while they were in Lund. The purpose of the cultural experiences was to teach students about international collaboration in science and engineering.

1.2 The Quarks

Quarks are believed be to the elementary particle which make-up nucleons such as protons and neutrons. Through studying this reaction scientists hope to gain an understand of how quark properties contribute to the properties of the nucleon. The advantages to studying this reaction are addressed in section 1.3 of this report.

Under the quark model, different arrangements of quarks form Hadrons. There are two known types of Hadrons: Baryons, and Mesons. An arrangement of three quarks is a Baryon such as a proton or a neutron and an arrangement of two quarks makes up a Meson such as a pion. The interaction of Quarks is governed by the quantum chromodynamic Lagrangian. like most second order partial differential equations the quantum chromodynamic Lagrangian has no analytic solutions. Although, two numerical methods are currently being research by the SAID group and the MAID group, chiral perturbation theory and model-independent partial-wave analysis. By experimentally studying the properties of the nucleon in terms of the quark model scientists hope to explore both of these numerical solutions. Quarks are particularly challenging to study because of color confinement.

	I		II		III	
Symbol	up u	down d	charm c	strange s	top t	bottom b
Rest Mass	2.4 MeV	4.8 MeV	1.27 GeV	104 MeV	171.2 GeV	4.2 GeV
Charge	$^2/_3$	$-^1/_3$	$^2/_3$	$-^1/_3$	$^2/_3$	$-^1/_3$
Spin	$^1/_2$	$^1/_2$	$^1/_2$	$^1/_2$	$^1/_2$	$^1/_2$

Table 1.1: Properties of the six different quark flavors organized by generations.

Quarks are particularly challenging to study because of color confinement. Color confinement is a property of quark theory which occurs because the color force is not a function of distance. In layman's terms, the force between the quarks does not diminish as they are separated. As a result, it requires and infinite amount of energy to separate the quarks.

This research focuses on the other properties of quarks which dictate to properties of the hadrons they form. Table 1.1 shows some of the properties of the six quark flavors which will be referenced in this section. There are also six antiquarks which have the opposite charge as well as other properties which are not dealt with in this report.

	Symbol	Charge	Spin
Proton	p	1	$^1/_2$
Neutron	n	0	$^1/_2$

Table 1.2: Some properties of well known nucleons.

Combinations of the up and the down quark make-up most of the matter people interact with. A combination of two up quarks and a down forms a proton and a combination for two down quarks and an up forms a neutron. Studying the quark make-up of nucleons can yield an understanding of how quark properties contribute to the properties of the nucleon. Charge is one example. It is trivial to see that the charge of the quarks add to the charge of a proton, and the charge of the quarks add to the charge of a neutron. The same is true for spin. The charge and spin of some common nucleons are in table 1.2.

1.3 Pion photoproduction

$$\gamma p \rightarrow n\pi^+ \qquad \gamma n \rightarrow p\pi^- \qquad \gamma p \rightarrow p\pi^0 \qquad \gamma n \rightarrow n\pi^0 \tag{1.1}$$

Pion photoproduction is an ideal reaction to study because it can be performed at energies where both experimental measurement and theoretical predictions can be made. This reaction was preformed between 165MeV and 200MeV. In pion photoproduction the quarks of the nucleon are directly rearranged to produce the pion. The four fundamental pion photoproduction reactions are listed in equation (1.1).

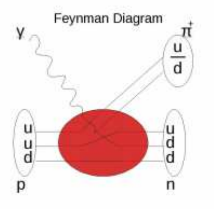


Figure 1.2: Feynman diagram of the $\gamma p \rightarrow n\pi^+$ reaction.

This experiment focuses on the $\gamma p \rightarrow n\pi^+$ reaction. In this reaction the interaction of a photon with the proton creates a down and an antidown quark. The antidown and one of the up quarks from the proton are ejected as a π^+. The remaining up and two down quarks are a neutron, so through this reaction the proton is transformed into a neutron and positivity charged pion is formed. Figure 1.2 is a Feynman diagram of this reaction. By considering table 1.1 it is trivial to see that the combination of quarks that form π^+ has charge of 1 and a spin of 0. Which is exactly what is observed.

1.4 Motivation

The ability of the bremsstrahlung photon tagging technique to create quasi-monochromatic light has provided scientists with the ability to make high resolution measurements with well know systematic uncertainties. Recently taking high quality measurement of the pion photoproduction reaction has become important in order to verify modern theoretical approaches such as Chiral Perturbation Theory (ChPT). By studying the cross section both near the threshold and away from the threshold scientists can gain an understanding of the momentum relation between the nucleon and the pion [1]. These result can then be compared with theoretical solutions.

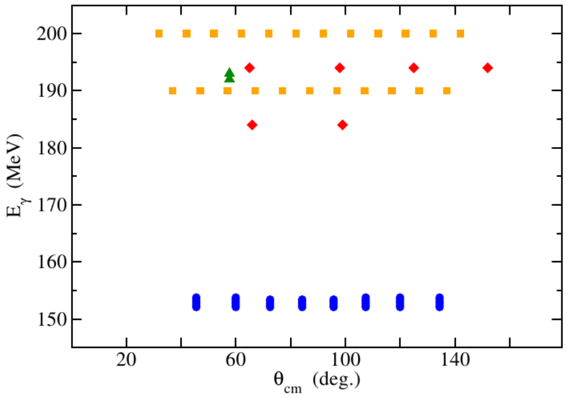


Figure 1.3: $\gamma p \rightarrow n\pi^+$ differential cross section for the photon energy below 200MeV [1].

The most recent data collected at the Saskatchewan Accelerator Laboratory (SAL) is in agreement with the predictions of ChPT but collecting additional data even closer to threshold will help with understanding the convergence of ChPT calculations. Furthermore, as illustrated in figure 1.3 very little data exists for the $\gamma p \rightarrow n\pi^+$ reaction away from the threshold [1]. Some of this date was collected by Dr. Fissum for his PhD thesis in 93 [2]. Combing data of this energy range with the data for neutral pion photoproduction will provide theoretical research groups such as SAID and MAID with information about the validity of their models and possible areas of improvement.

Chapter 2

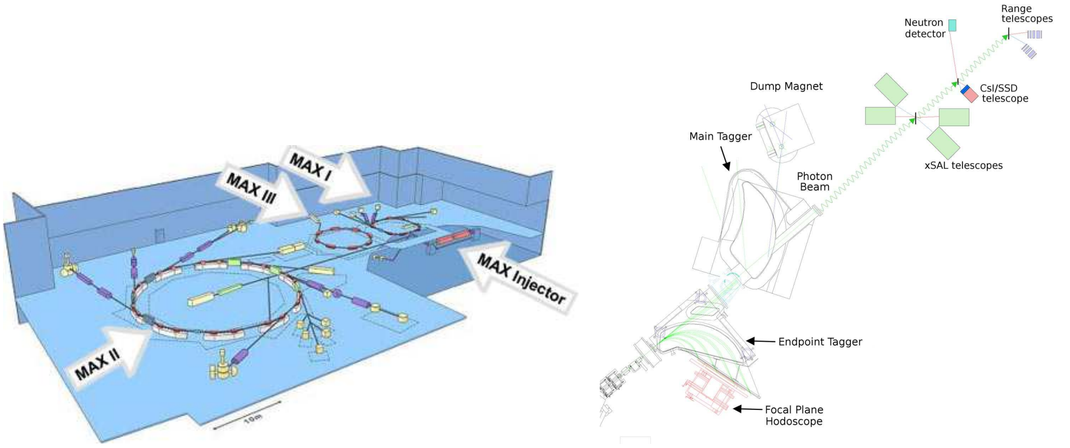
Experimental Procedure

2.1 Accelerators

For this experiment the MAX I synchrotron accelerator was used to stretch the 200ns pulse into a 100ms beam. The MAX-injector can operate at up to 10hz so the beam can be continues under ideal conditions. Using a continues beam is important to getting a steady beam of photons for the experiment. The MAX I ring receives the pulse of 200MeV electrons from the MAX-injector which consists for the electron gun and two linear accelerators. The electron gun emits the electrons from the cathode at 2MeV. The electrons are then accelerated by both linear accelerators where the electrons gain 200 MeV. At this point the electrons travel to MAX I to be stretched and sent to the cave. A diagram of the MAX-lab accelerators is shown in figure 2.1(a).

2.2 The Tagger

As addressed in section 1.4 there is no data for the 165 - 180 MeV region. As a result the newly upgraded endpoint tagger at MAX-lab is ideal for this experiment. The new endpoint tagger is the SAL focal plane array which was transferred to MAX-lab after SAL phased out nuclear physics experiments to make way for the Canadian Light Source in 1997. The tagger can be seen in the experimental set-up in figure 2.1(b). The tagger is used to detect the energy of the photons used in the $\gamma p \rightarrow n\pi^+$ reaction.



(a) A diagram of the MAX-lab showing the synchrotron accelerator rings MAX I, MAX II, and MAX III and the linear accelerator MAX-injector.

(b) Schematic of the experimental setup showing the MAX-lab tagger as well as the three detector systems used for the pion photoproduction measurements: xSAL, Csl/SSD, and RANGE.

Figure 2.1

The endpoint tagger uses a uniform magnetic dipole to bend the electrons into the focal plane array [3]. The focal plane consist of two adjacent arrays of hodoscopes which detect electrons. The amount the electron's path is bent by the magnetic dipole is proportional to the amount of energy the electron has. As a result the energy of the electron can be determined by where it hits the focal plane. From this the energy of the photon interacting with the target can be calculated. For this experiment the tagger was set up to tag photons with energies between 145MeV and 180MeV with bin of 1MeV.

2.3 xSAL

One goal of this experiment was to achieve less error then previous measurements. The xSAL telescopes where particularly good for this because they have a well understood systematic error [1]. The xSAL telescopes were originally built at SAL and are made up a plastic scintillator (ΔE detector) and a thicker plastic scintillator stopping power detector (E detector). The germanium count was used to detect the stopping energy, as well as pion decay. Pion decay is addressed in more detail in section **??**.

Four xSAL telescopes were used for this experiment. The xSAL placement can be seen in figure 2.2. The line down the center denotes the beam line.

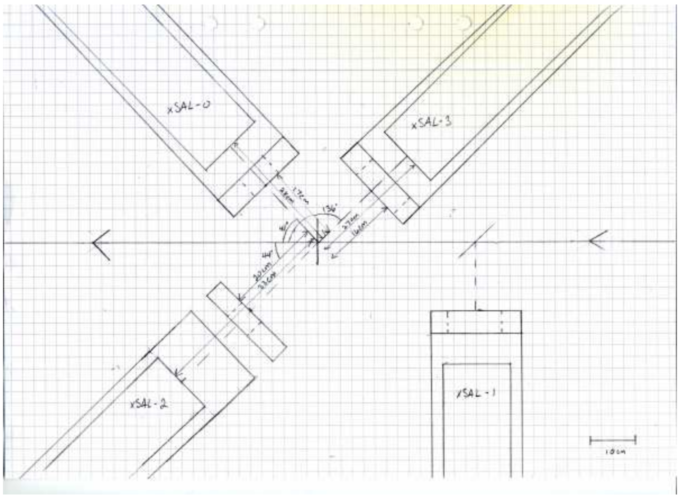


Figure 2.2: The layout of the four xSAL detectors. The line down the center denotes the beam line and the lines crossing the beam line denote the targets. (Hand drawn by D.J. Kelleher

2.4 The targets

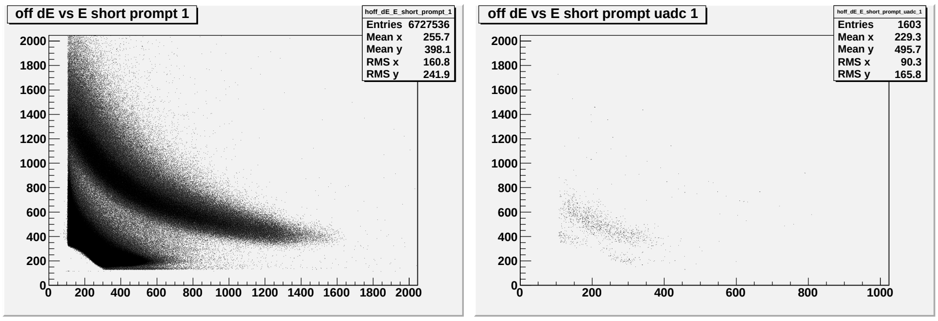
Two targets were used for this experiment a CH_2 target and a C target. The CH_2 target was used to provide the proton for the $\gamma p \to n\pi^+$ reaction while the C target was used to subtract background. The CH_2 and C targets had approximatly the same density and weight of carbon so that statistics could be compared.

Chapter 3

Analysis

3.1 Particle Identification

One crucial part of this experiment was particle identification. One typical method of particle identification is stopping power, this method is effective at identifying particles based on the mass. Figure 3.1(a) shows some of the common particles and their location in the stopping power plot. Using the stopping power method was not effective at isolating pions because the background events swamp the pion events. It is clear looking at the event numbers of figure 3.1 that some simple analysis reduces six million events to about a thousand events. Figure 3.1(b) shows the pion candidate events in an intermediate stage of analysis.



(a) ΔE vs E short before analysis. The pion events are swamped by the background events.

(b) ΔE vs E short after some analysis. This is and example of some pion candidate events.

Figure 3.1

3.1.1 Prompt Peak

In order to ensure that the events begin analyzed are tagged events the data was cut on the tagger TDC. In order to do this the tagger channels where offset from their natural value to form a prompt peak across all channels. Figure 3.2 shows the aligned peaks of the tagger TDC. This plot only shows events in the tagger so the noisy background is explained by background events interacting with the focal plane. Another method which was used to reduce the background events in the tagger was redundant hodoscopes as discussed in section 2.2. This was effective at reducing background by requiring tagging electrons pass through both hodoscopes. Thus ensuring that the electron came from the bending magnet rather then a random event in the room.

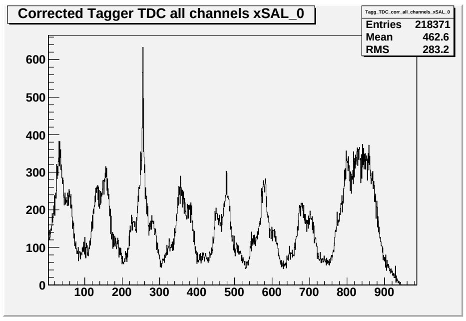


Figure 3.2: A plot of the time to digital convertier output for all tagger channels. The channels were “normalized” to peak all at the same value.

3.2 Energy

One well known method of pion identification is to use decay energy. The process of pion decay ($\pi^+ \rightarrow \mu$) has a well known energy of 4.12MeV and mean life time 26ns. This section will focus on using the decay energy to identify pions and section 3.3 will address mean life time based methods as verification of the energy based analysis. This method was used by Dr. Fissum in his dissertation [2].

3.2.1 Muon QDC Cut

As mentioned above pions have a well known decay energy of 4.12MeV. Using two differently timed QDCs this energy can be recorded in one QDC value an not the other. Figure 3.3 shows the timing difference between the two QDCs. This is an effective way to isolate pions from the background because the background particles do not decay. As a result the background particles only deposited the energy associated with the first spike in figure 3.3 but pions deposit both.

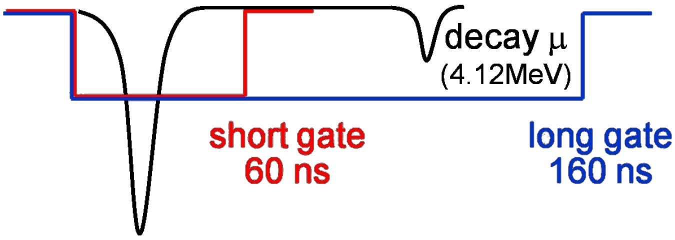
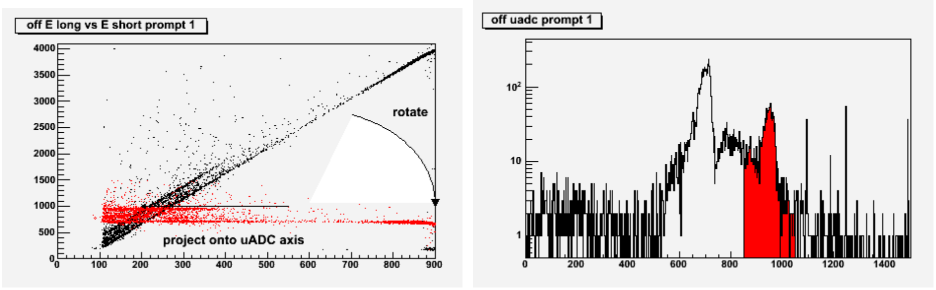


Figure 3.3: Illustration of the energy deposited in the short and long gate QDCs because of $pi^+ \rightarrow \mu$ decay.



(a)

(b)

Figure 3.4

Using this knowledge, plotting the long gate vs the short gate energy is an effective way to identify pion candidate events. In this method pion candidate events appear as a parallel, offset line to the background. This can be seen in figure 3.4(a). Now by rotating an projecting the long vs short plot it is possible to cut on the muon decay events leaving only pion candidate events. The rotation can be seen in figure 3.4(a), and the projection can be seen in figure 3.4(b). The red in the muon QDC shows which events where kept during the cut. The results from this cut can be seen in figure 3.1(b). The next step in the analysis process is the ΔE - E cut but additional refinement of this method will be addressed in 3.2.3.

3.2.2 ΔE - E Cut

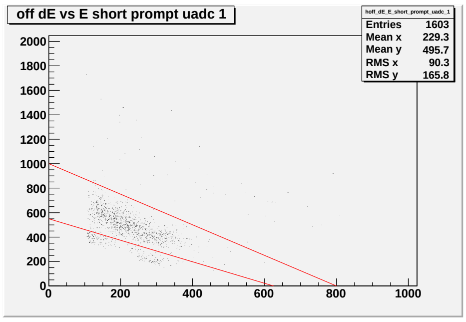
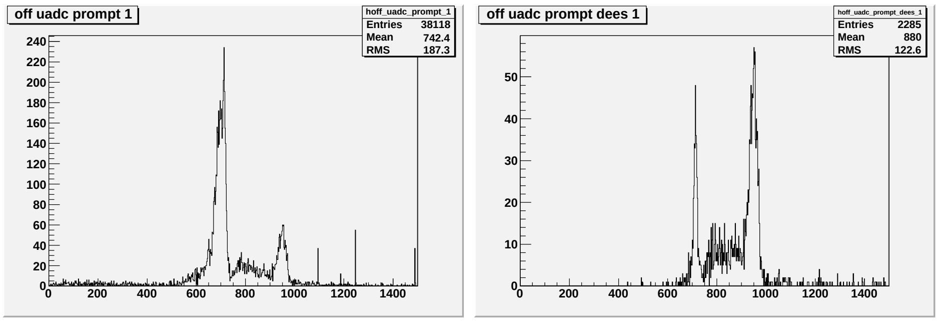


Figure 3.5: Cut on the results of the muon QDC cut. This cut was cut on the raw data but the cut was made based on these results.

From the results of section 3.2.1 a new cut was devised to help refine the analysis technique. Despite the appearance of figure 3.5 the cut was done on the raw data not the results of the muon QDC cut but the result were used to define to cut lines. The idea is to cut the raw data for events that are in the typical pion region of the stopping power plot. By limiting the energy most of the coincidence events can be filtered out. One example of a coincidence event is a proton striking the detector, and an electron also striking the detector withing the long gate 160ns. The use of this cut is to refine the cuts on the muon QDC. Figure 3.6 show the muon QDC before and after the ΔE vs E cut. Note that the muon QDC is not long log plotted. Also note that the number of events in the muon QDC plots is reduced by an order of magnitude from this cut.



(a) (b)

Figure 3.6

3.2.3 Iterations

Additional iterations of the above analysis technique will yield better statistics. Using figure 3.6(b) the muon QDC cut can be refined to better isolate pion events. From that the ΔE - E cut can also be refined. This process can continue until both cuts are completely optimized to isolate pions.

3.3 Time

As mentioned in section 3.1 both mean life time and decay energy can be used to isolate pions for the background. As a result the mean life is used as a verification method.

Chapter 4

CSUMS

This chapter will include information as well as personal reflection on the CSUMS program.

4.1 Root: Some things I Learned

Why use Root? having never used and object oriented programing language Root posed a particular challenge while addressing this problem but is ideal because of it's speed saving and loading large amounts of data. Root is a C++ derivative which uses a hierarchical method for storing data. What this does is it allows the user to access large arrays of data with out scanning the entire data file into memory. This principle is similar to a journaled file system.

Using Root was challenging not only because it required me to learn how to use an object oriented programing language but it also required i used linux. This became a particular problem when modern distributions removed needed header files from some of the required libraries. In order to remedy this I was required to build my own version of gentoo linux (A project which almost consumed my spring break).

4.2 Reflection

The CSUMS program (not just this semester), was an excellent opportunity to grow as a student and as a researcher. I still regularly use the Matlab skills I learned in the first semester as well as other valuable skills such as latex. The most important thing CSUMS ever taught me was how to speak publicly. I believe this is the most important part of the course although I would have one of the two research talks actually count for the grade. I think it may be more effective to evaluate students ability to speak as well as suggest improvements.

References

[1] G.V. O'Rielly. Charged pion photoproduction from threshold up to the first-resonance region. Research Proposal NP014, MAX-lab, 2004.

[2] K.G. Fissum. *Inclusive Photoproduction of Positive Pions.* PhD thesis, University of Saskatchewan, 1993.

[3] Magnus Lundin. Tagged photon energies for the et. Technical specifications, MAX-lab, 2008.