PRODUCTION OF EXOTIC AND STRANGE MATTER AT JEFFERSON LAB

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Abstract

The Standard Model of particle physics predicts the existence of a special kind of particles that have not yet been conclusively observed. The properties of these "exotic" particles can help to understand why one of the fundamentals building blocks of matter ("quarks") are impossible to observe in isolation. At Jefferson Lab, we are conducting an experiment that plans to produce those exotic particles when a beam of high–energy photons collides with nuclei of hydrogen atoms. We use the Cebaf Large Acceptance Spectrometer (CLAS) to measure the photo–produced particles. Other particles, made from pure "strange" quarks, will also be produced and studied in this experiment. The importance of these measurements for the current understanding of the structure of matter, and the working of the experiment are described in this paper. Preliminary results from data obtained during the 1999 experimental period are briefly presented.

INTRODUCTION

Most of the visible matter in the universe is made of protons, neutrons and electrons. In the 1960s scientists realized that protons and neutrons (called *nucleons*) are made of smaller objects called *quarks*. Quarks come in six varieties ("flavors") called *up, down, charm, strange, top* and *bottom*. Protons and neutrons are made of three quarks, a mix of the *up* and *down* quarks. The rest of the quark's types are the components of a very rare kind of matter, normally with ephemeral lifetimes. These rare particles live for such a brief period of time (about 10^{-23} seconds!) that it is currently impossible to detect them directly in the laboratory. Scientists need to look through their debris (or the debris of their debris!) to infer their existence. However, sometimes "debris particles" may have been produced by the interaction of the beam and the target without the expected rare meson having been produced. Then, scientists need to measure the rate of production of the debris, looking for "*resonance peaks*" (sudden increases on the rates of production of the debris particles as function of their collective masses). For a given beam–target combined mass, more debris particles will be produced due to the production of the rare particle than during normal "background". Resonances and particles are interchangeable in the jargon of the particle physicist.

Resonances (particles) are described in mass histograms by their peak position (mass) and by the "width" of the distribution about the peak. A given resonance can decay to many other particle (debris) sets. This "set of debris" is called a decay channel. In general, the more channels available to the resonance the shorter its lifetime. Resonances with narrow widths are easy to identify. There are many resonances, (about a hundred up to a mass of 2 GeV/c^2) therefore resonances often overlap. To disentangle this complicated overlap of resonances is not easy. We need to include more information about the debris (such as the angular distribution of the detected debris) and include models on the production and decay mechanisms. Finally, a statistical multidimensional fit, *called Partial Wave Analysis*, is tailored to the observed properties of the debris using a set of expected resonances and production models [1,2].

The "Standard Model of particle physics" describes the universe as made of particles and their interactions [3]. The most important interaction among quarks is the *strong interaction*. The strong interaction has a very short range, it can only be felt inside the nucleon, and only among the quarks. *Quantum Chromodynamics (QCD)* is the theory describing strong interactions. QCD tells us that quarks have a property called "color charge" (similar to the electric charge). Quarks are colored objects susceptible to the strong interaction. Colorless objects (i.e., protons and neutrons) are not. The strong interaction consists of the exchange of particles called *gluons* [4].

Gluons themselves have color charge, therefore, gluons can also attract each other through the strong interaction. In contrast, the electromagnetic interaction between opposite charged particles diminishes with the inverse of the distance squared between them, as it consists of the exchange of uncharged photons that spread around charged particles. Because gluons can strongly interact, they are not evenly spread about the color−charged particle (they will be attracted to each other). The result is a "tube−like" distribution of glue between two color−charged particles. As we try to separate the two particles, the tube stretches, becoming more and more difficult to separate the particles. The net result is that the strong interaction increases with the distance between charges. If we put enough external energy (force) to try to separate the particles, we will eventually break the tube. Each broken end of the tube will pick up a quark−anti−quark pair from the vacuum [5], thus producing two particles. The conclusion is then, that colored objects can not be observed in isolation. This property of the strong force is called "*confinement*". Quarks exist in nature only as groups that are colorless.

A quark−anti−quark pair is called a "*meson*". It is the simplest colorless aggregate of quarks and therefore being ideal for the study of the strong interactions.

In the 1950s, several "*strange*" particles (that were not expected by the prevailing theories of the time) appeared in experiments observing secondary cosmic rays (particles showering from space). These were particles that were not part of "normal" matter. We know now that they are made of a rare kind of quarks, *the strange quark*. These particles can be produced now in accelerators using high−energy interactions between the most common types of particles (i.e. electrons and protons).

The family of mesons formed by pure strange quarks (strange + anti−strange, $s\overline{s}$) is called "*strangeonia*". The members of this family are defined by the $s\overline{s}$ pair energy levels. Excited states (higher energy levels) of the $s\overline{s}$ pair will manifest as a heavier meson. It is expected that photo−production will be an excellent way to produce these $s\overline{s}$ states [6].

Very little is known about the $s\overline{s}$ states. The only well−known state, the strangeonium ground state, is the *phi* particle, ϕ, with a mass of 1020 MeV, a very "narrow" state (width of about 4 MeV). The first radial resonance of the ϕ family has been reported at 1680 MeV. However, there is no conclusive experimental evidence (a complete determination of its quantum numbers) to claim that this resonance is a pure $s\overline{s}$ state [7].

Another manifestation of the self−interaction of the gluon is the existence of pure gluonic bounded states (*glueballs*) and hybrid mesons (quark+antiquark+gluon states), referred to, collectively, as *exotic mesons* [8]. An irrefutable experimental evidence for the existence of an exotic meson would be the determination of its properties. Mesons are characterized by several "*quantum numbers*": i.e., their internal total angular momentum (J), parity (P, their appearance when their constituents are spatially switched by their center) and charge conjugation (C, their identity when particles are switched by their anti−particles). A given meson is then represented by a set of J, P and C values often written as J^{PC}. A $q\overline{q}$ pair can not form any combination of these numbers. Combinations such as $J^{PC} = 0^{--}, 0^{+-}$, $1^{-+}, 2^{+-}, etc.$ only can be achieved with extra particles, i.e. when an extra gluon ($q\overline{q}g$) is present. An observation of a resonance with these quantum numbers will give a clear indication of a meson beyond the simple $q\overline{q}$ pair model.

In June of 1998, the E852 collaboration at Brookhaven National Laboratory announced the observation of a $J^{PC} = 1^{-+}$ exotic meson decaying to a three pions ($\pi^+\pi^-\pi^-$) final state, with a mass of about 1600 MeV [9]. E852 used a high−energy pion meson beam (18 GeV) incident on hydrogen nuclei to produce the exotic meson candidate. There are several experimental and theoretical difficulties inherent with the identification of those states. Experimentally, a normal $q\overline{q}$ state could mimic an exotic state due to imperfections in the detection technique (insufficient acceptance and/or statistics). If the rate of production of the exotic is very small, relatively larger and close normal resonances may "leak" into the exotic resonance. A clear theoretical understanding is also complicated, since meson mixing can also produce similar exotic states. The "flux−tube model" and, recently, "lattice QCD" calculations have suggested a mass of about 1900 MeV for the lowest mass exotics. The E852 observations seem experimentally clean but fall below the masses expected by the theory. Theorists have speculated that some meson mixing is present in those observed states. More experimental data, especially if it is obtained with a different production mechanism (i.e., if a photon beam is used) could provide further understanding of those states.

CLAS EXPERIMENT

The Thomas Jefferson National Accelerator Facility, or Jefferson Lab (JLab), is a nuclear physics research laboratory built to probe the quark structure of the nucleus. A recirculating pair of linear accelerators accelerates electrons up to energies close to 6 GeV [10].

The CLAS (Cebaf Large Acceptance Spectrometer) [11] detector at Jefferson Lab's Hall B was designed to study multi−particle final states with a combination of relatively large acceptance and moderate momentum resolution. A schematic representation of the detector inside Hall B is shown in figure 1. CLAS is a toroidal magnet spectrometer with six super−conducting coils. The electrons coming from the accelerator are used to produce high−energy photons (at almost 6 GeV) that subsequently collide with hydrogen nuclei (target) at rest in the center of the detector.

The debris produced in this high−energy collision are detected in almost all directions by several layers of electronic detectors. The CLAS detector consists of drift chambers, gas Cerenkov counters scintillation counters and sampling Pb−Sci calorimeters arranged in a six−gap geometric structure between the torus coils.

The beam of high−energy photons is produced by a phenomenon called "bremssthralung", when the incident primary electrons pass through the electric field of matter and are de−accelerated producing radiation (photons). The de−accelerated and deflected electrons are then tagged by a "tagger" spectrometer. The energy difference between the incoming electron and the deflected electron, measured in the tagger spectrometer allows a very precise determination of the photon energy (at about 0.1 %) [12].

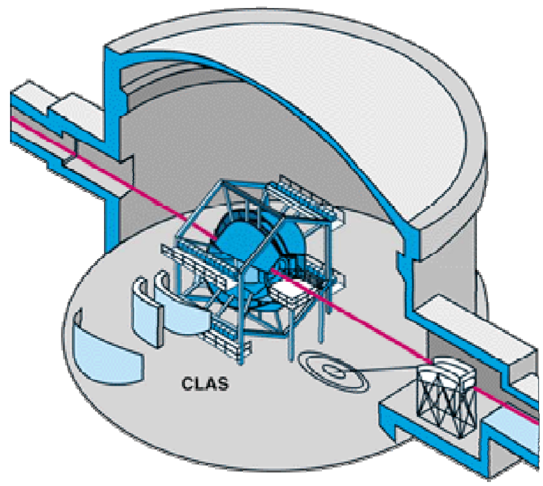

Figure 1: The CLAS detector at Hall B. The red line represents the incident particle beam (from the right). Some detectors are shown detached from the main CLAS body for better view.

Experiment 99−005 [13] uses CLAS to search for photo−produced mesons. It requires photon incident beam energy greater than 5 GeV. The main goals are the search for exotic mesons and the determination of the quantum numbers of strangeonia ($s\overline{s}$) states. The focus is on the $\rho\pi$ and KK* meson final states in the 1 to 2 GeV mass range. Those final states (debris from the original resonance) correspond to the signatures for the 1^{-+} exotic state [$\pi_1(1600)$] observed by E852, and for the first radial excitation of the $s\overline{s}$ [φ (1680)].

The experiment collected data during July−August, 1999. It will take data again during most of August 2001, with an expected improved configuration capable of increasing the available statistics by an order of magnitude. Analyses of the 1999 data are still in progress. A brief summary of the current status of the 1999 data analyses follows.

ANALYSES STATUS

EXOTICS

REACTION: $\gamma p \rightarrow n\pi^+\pi^+\pi^-$

We have two possible topologies for the study of this channel. In the first, we measured the three pions ($\pi^+\pi^+\pi^-$) in CLAS, and reconstruct the neutron through the missing mass technique. This technique is based in the knowledge of the incoming photon beam energy and the mass of the target. We make a balance of energy (mass), since we know what is coming into the collision, we can calculate what is "missing (mass)" among our debris.

Figure 2 shows the missing mass squared spectrum off of the three reconstructed pions. We observe a clear peak about the neutron mass. After a mass cut around the neutron mass (940), we are left with 40106 events, those events should contain then a set of $n\pi^+\pi^+\pi^-$ final states. The $\pi^+\pi^-$ mass spectrum of these events is shown in figure 3. The ρ^0 (770) and f_2 (1270) mesons are both clearly evident in the mass spectrum.

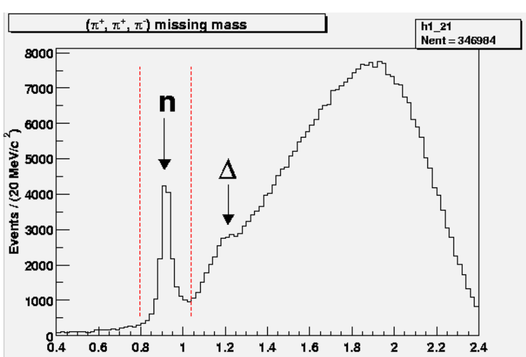

Figure 2: mass square off of $\pi^+\pi^+\pi^-$.

Figure 4 shows the mass spectrum of the system $\pi^+\pi^+\pi^-$ for $\gamma p \rightarrow n\pi^+\pi^+\pi^-$ exclusive events. The shape of the spectrum is determined mainly by acceptance: because the negative π is in–bending in CLAS, and most of them go through a region of CLAS where there is no possibility of detection (the beam pipe). High three pion masses have higher reconstruction efficiencies since the negative π flies further from the beam pipe. At the interesting meson mass of about 1600 MeV/c^2 we currently have about 250 events per 20 MeV/c^2 mass bin. We need to collect more events (statistics) to start our partial wave analysis in this mass region.

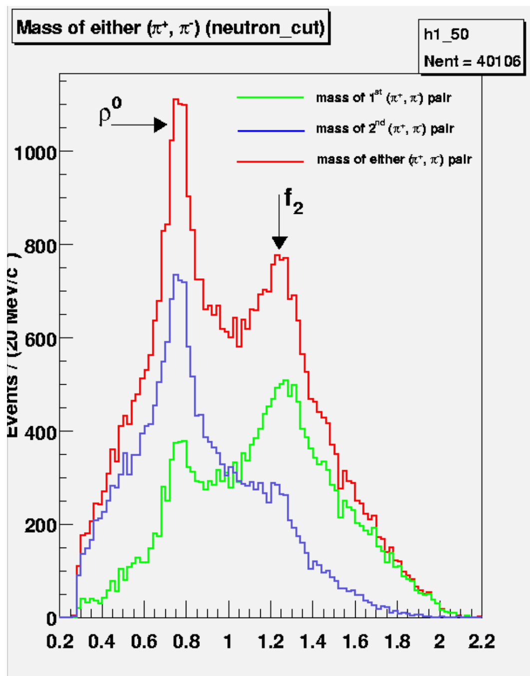

Figure 3: mass of $\pi^+\pi^-$.

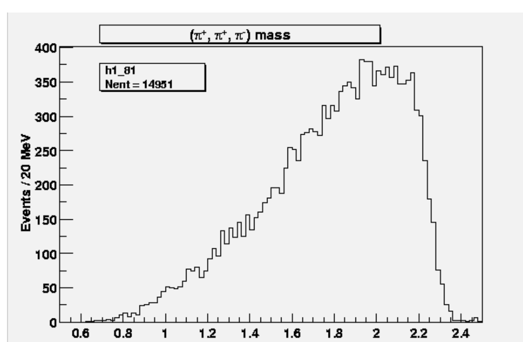

Figure 4: mass spectrum of the system $\pi^+\pi^+\pi^-$ for $\gamma p \rightarrow n\pi^+\pi^+\pi^-$ exclusive events.

Another way to detect this topology is to observe the neutron in the CLAS forward calorimeter. The neutron has a high interaction probability of about 30 % in the forward electromagnetic calorimeter. The timing information in the calorimeter is sufficient to determine the neutron momentum through time–of–flight. However, the resolution in the calorimeter is much worse and the missing mass technique (to reconstruct the negative π) gives less precise results.

REACTION: $\gamma p \rightarrow p\pi^{+}\pi^{-}\pi^{0}$

In this channel we observe the proton and the π^{+}, and in addition either the π^{0} (actually, its decay into two photons) sin the electromagnetic calorimeter or the π^{-} in the CLAS drift chambers. The mass of the two–gamma system, in figure 5, shows a clear π^{0} peak. Also, the missing mass squared off of the $p\pi^{+}\pi^{-}$, shows a clear π^{0} peak (no shown).

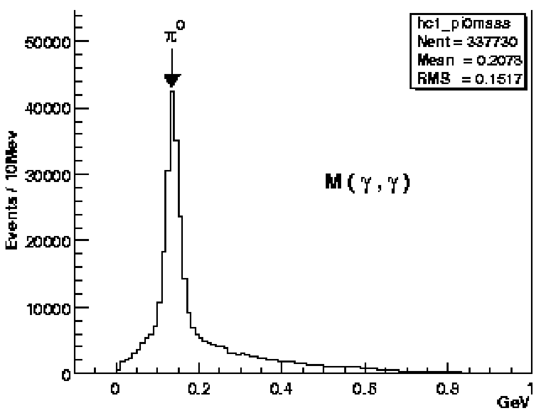

Figure 5: γγ effective mass.

Figure 6 shows the missing mass squared spectra off of the $p\pi^{+}\pi^{0}$ system, where a clear π^{-} is observed. Figure 7 shows the missing mass squared spectra off of the $p\pi^{+}\pi^{-}$ system for data where the π^{-} is observed in the CLAS

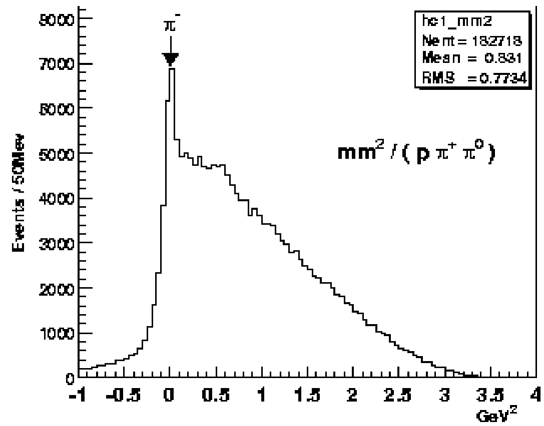

Figure 6: squared mass off the $p\pi^{+}\pi^{0}$ system.

detector. Here, one can see a clear π^{0} signal, as well as the η and ρ^{0} mesons (all decaying to γγ).

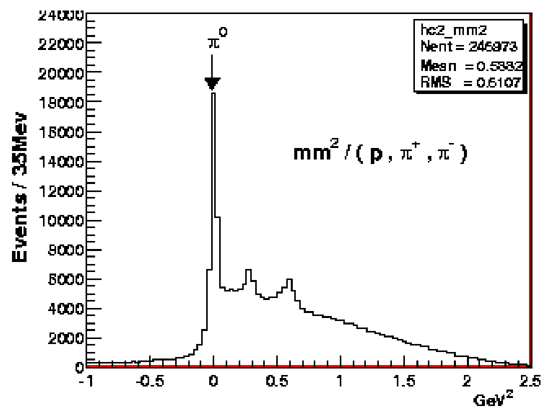

Figure 7: squared mass off the $\gamma p \rightarrow p\pi^{+}\pi^{-}$.

Figure 8 shows the $p\pi^{+}, p\pi^{0}, p\pi^{-}$ system mass distributions for $p\pi^{+}\pi^{0}$ where π^{-} is missing. We can observe "*baryonic resonances*" (heavy nucleons) for example, resonances where the proton produces an intermediate baryon in

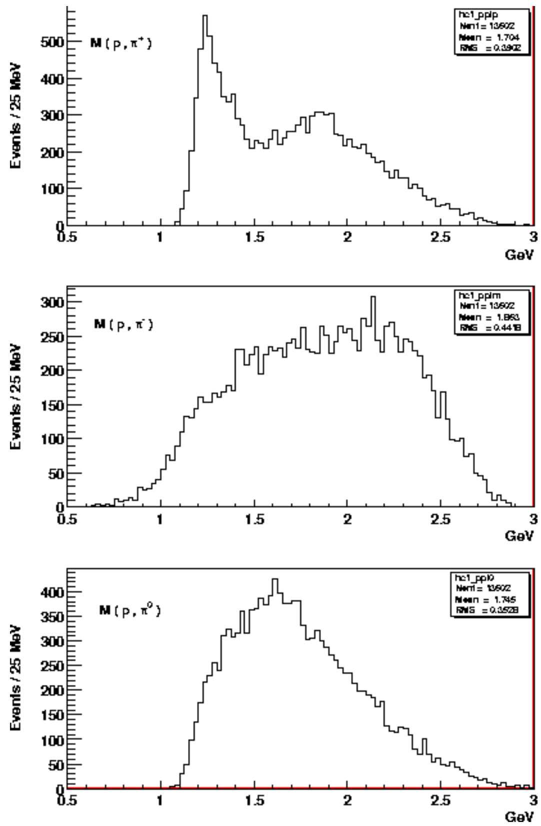

Figure 8: $p\pi$ mass distributions: $p\pi^+\pi^0$ detected.

$\gamma p \to \Delta^{++}\rho \to p\pi^+\pi^+\pi^-$, an important background to our exotic search. Only the Δ^{++} resonance is clearly seen in the mass spectra.

Figure 9 shows the same mass distributions for the $p\pi^+\pi^-$ where π^0 is missing. In this topology the baryon resonance mass spectra is richer. A cut of ± 70 MeV/c^2 around the Δ^{++} mass has been imposed to clean the meson sample.

The mass acceptance for these three topologies is considerably different. The mass spectra of the $p\pi^+\pi^-\pi^0$ system, for each topology, is shown in figure 10. The same data, cutting also around the ρ^0 events is shown in figure 11.

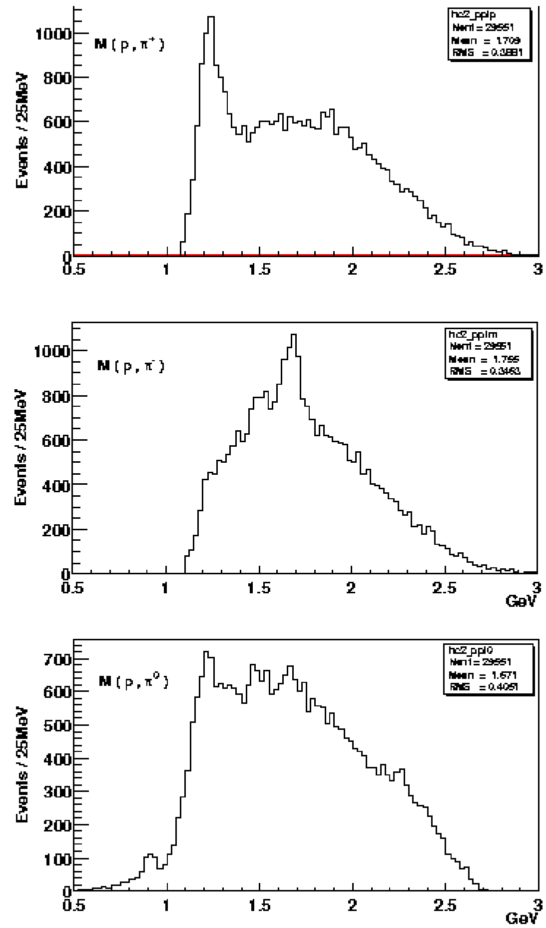

Figure 9: $p\pi$ mass: $p\pi^+\pi^-$ detected.

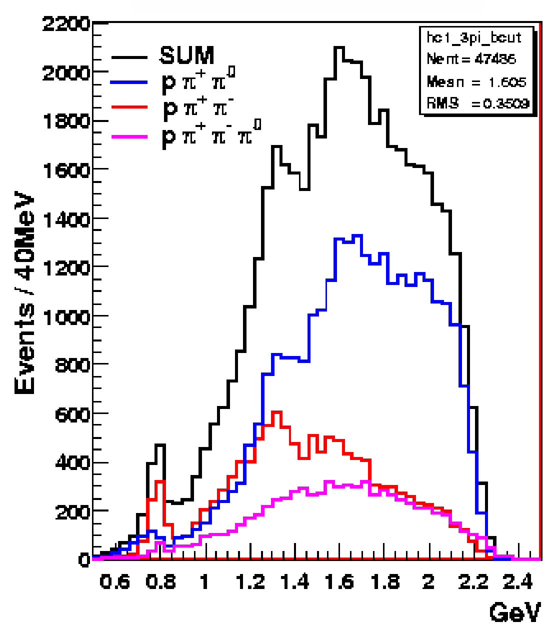

Figure 10: $\pi^+\pi^-\pi^0$ mass spectra with Δ^{++} cut (see text).

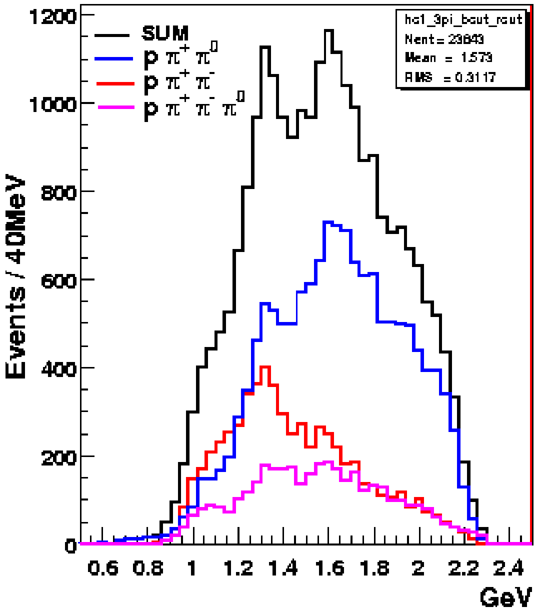

Figure 11: $\pi^+\pi^-\pi^0$ mass spectra with Δ^{++} and ρ cut.

We see a "mass peak" (figure 11) in the region of about 1600 MeV where the expected exotic state has been observed. We will collect more data in our upcoming experimental run to be able to make a full partial wave analysis in this region.

STRANGEONIA

Strangeonia debris contain several types of K–mesons (these are a mix of "normal" up and down quarks and the "strange" quark). Therefore, to study strangeonia is necessary to have a good mean of K identification. Mostly, a way to distinguished the K from the more common π mesons.

We use a timing measurement for that purpose. For the same energy (momentum), K's, being heavier will take longer to run the same distance. We measure this "time–of–flight" distance between a very fast counter and the interaction vertex, about 4 m apart in the detector.

In order to achieve the highest statistics needed for the spin–parity identification of these meson states, the experiment was run at a high beam flux rate (about 5×10^7 photons/second). As a result, the data contain a high number of "accidental triggers", recorded events where the photon producing the event was misidentified. However, a careful analysis of the event signal timing showed that many triggers result from an interaction in one beam bucket, while the triggering tagged high–energy photon comes from another beam bucket.

The tagger system determines the start time for time–of–flight (TOF) measurement (a.k.a. vertex position), all TOF measurements for these events are distorted by about 2 nanoseconds (the next or previous beam bucket). This result not only in a large background under pion events, but also significant leakage of pions into the kaons, which completely obscures the kaon signal. We have developed an algorithm which looks at two particle correlation in the β (velocity/c) versus p (momentum) curve to determine if the tagger time corresponds to the correct time–of–flight for both particles. A χ^2 is calculated over the sum over both TOF masses for three different beam bucket times, (0 , ± 2 and ± 4 nanoseconds offset from the trigger photon).

Events are retained only if the high–energy photon tagger time is identified as the most likely. Figure 12 shows the resulting β versus p curve for all positive charged particles after this rejection. The kaons, previously obscured totally by pion leakage, is now clearly delimitated for momentum up to 1.5 GeV/c. The time–of–flight mass spectra is shown in figure 13 for positive particles with momenta less than 1.5 GeV/c.

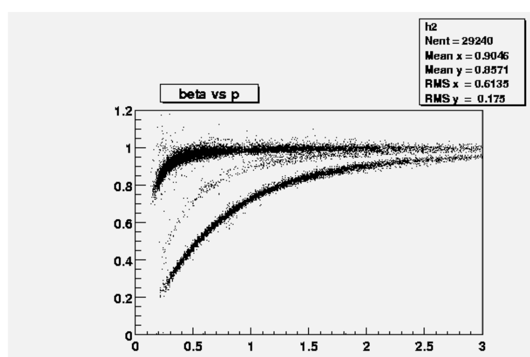

Figure 12: β versus p for all positive charged particles after analysis rejection (top curve are π's, middle K's and bottom protons).

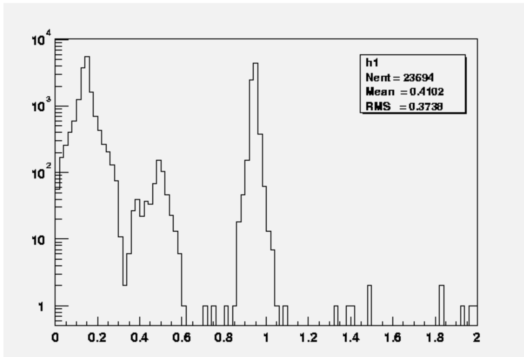

Figure 13: mass (GeV/c^2) as determined from TOF and momentum for positive tracks.

$\gamma p \rightarrow pK^+$ INCLUSIVE

We have a large sample of data where a proton and a K$^+$ are detected in CLAS and identified through time–of–flight. In figure 14 we show the missing mass squared distribution off of the proton and K$^+$.

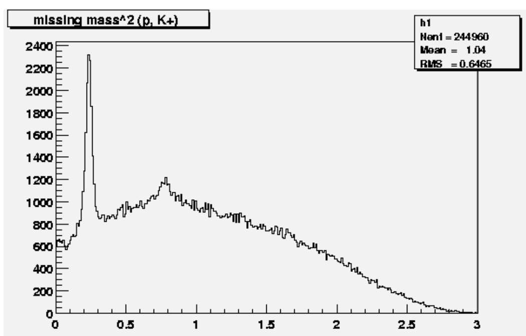

Figure 14: Squared mass of p K$^+$.
We can clearly discern the K$^-$, and also a bump at the K*(890). Figure 15 shows the meson mass for the K$^+$K$^-$ events (top), and K*(890)K$^-$ events (bottom). In the exclusive pK$^+$.K$^-$ events we can clearly see the ϕ(1020) resonance, but there are no discernible structures in the K$^+$K*(890) mass distribution. This is perhaps the result of K* being poorly defined from the background. We just started the analysis of the $\gamma p \rightarrow pK^+K^-\pi^0$ (missing K^-) channel. We expect to use this channel to study the first radial excitation of the ϕ at above 1680 MeV.

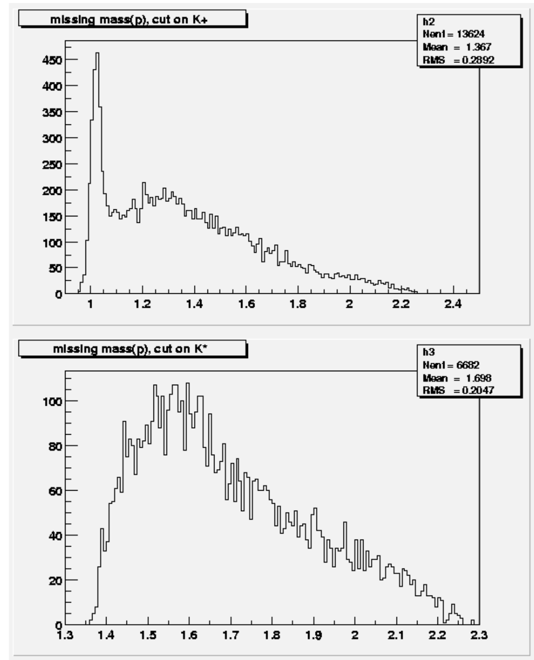

Figure 15: mass of K$^-$ K$^+$ (top) and of K^{*-} K$^+$ (bottom).

SUMMARY

Meson spectroscopy (the study of the "meson" family of particles) is of particular interest to understand strong interactions. The elusive exotic mesons, when clearly identify, will provide an excellent system where to test the theory. In particular, it will illuminate the internal workings of QCD confinement. The strangeonia family is very poorly known. This meson family could give very clean examples to study decays and meson production models. Photo–production has rarely been used to produce mesons. Recently, it has been speculated that photo–production could be very advantageous for the production of exotics and strangeonia.

The study of exotic mesons and strangeonia has started at CLAS in Jefferson Lab using photon beams. The CLAS detector has sufficient acceptance and resolution to obtain a very good sample of meson decaying to few body final states (about four). Based on the preliminary analysis of data taken during 1999 and briefly reported in this paper, we believe that experiment 99–005 can produce a meson spectroscopic analysis of similar quality to those of the most successful experiments in the field, for example, E852 at Brookhaven.

We are preparing a new experimental run for August 2001. We are planing several improvements in the data taking procedure (i.e., we will run with reduced magnetic field, increased beam flux, etc.). Taking into account all these factors, we feel that we will be able to improve our sensitivity an order of magnitude.

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