Meson Spectroscopy at JLab@12 GeV

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Abstract. Meson, being the simplest hadronic bound system, is the ideal “laboratory” to study the interaction between quarks, understand the role of the gluons inside hadrons and to investigate the origin of color confinement. To perform such studies it is important to measure the meson spectrum, with precise determination of resonance masses and properties, looking for rare $q\bar{q}$ states and for unconventional mesons with exotic quantum numbers (i.e. mesons with quantum numbers that are not compatible with a $q\bar{q}$ structure).

With the imminent advent of the 12 GeV upgrade of Jefferson Lab a new generation of meson spectroscopy experiments will start: “Meson-Ex” in Hall B and “GLUEX” in Hall D. Both will use photo-production to explore the spectrum of mesons in the light-quark sector, in the energy range of few GeVs.

1. Introduction

The phenomenology of hadrons and in particular the study of their spectrum led more than forty years ago to the development of the quark model, where baryons and mesons are described as bound systems of three quarks and of a quark-antiquark pair, respectively. While this picture still holds and has been proven to reproduce many features of the hadron spectrum, now we know that the hadron mass cannot be explained only in terms of the quark masses, but it is mainly due to the dynamics of the gluons that bind them. Measuring the spectrum of hadrons, studying their properties and their inner structure is therefore crucial to achieve a deep knowledge of the strong force.

Mesons, being made by a quark and an anti-quark, are the simplest quark bound system and therefore the ideal ”laboratory” to study the interaction between quarks, understand the role of gluons, and investigate the origin of confinement. The Constituent Quark Model predicts the existence of multiplets of mesons with similar properties and masses, that are classified according to their total angular momentum $J$, the parity $P$, and charge conjugation $C$. While most of the lowest mass states have been clearly identified and studied [1], several open issues related to the mass hierarchy and decays of excited states remain and still await for a experimental investigation. In addition phenomenological models [2, 3, 4, 5, 6, 7] and lattice QCD calculations [8, 9] suggest that states beyond the simple $q\bar{q}$ configuration, as hybrids (qqg), tetraquarks ($qq\bar{q}\bar{q}$), and glueballs, should also exist. If it would be the case, a much richer spectrum than that predicted by the quark model should be expected and, in particular, new meson multiplets corresponding to these unconventional configurations should be observed.

Hybrid mesons are of particular interest as they are the cleanest experimental signature for the presence of gluons in the dynamical mass generation process. A precise determination of
their spectrum and properties can provide a unique opportunity to study the role of the glue and to understand the phenomenon of confinement.

An unambiguous identification of these states can in general be rather difficult, since they can mix with ordinary mesons having the same quantum numbers ($J^{PC}$). However, the additional degrees of freedom present in these states can also lead to exotic quantum numbers that are forbidden in $q\bar{q}$ systems, and therefore provide a unique signature of their unusual structure.

Figure 1. Recent lattice results from JLab lattice collaboration [9] for the low-lying isovector mesons. Masses are given in units of the $\Omega^-$ baryon. States within the red box have exotic quantum numbers.

2. Contemporary Meson Spectroscopy Experiments

As per today the experimental determination of unconventional mesons is rather confused, since there are not clear, unambiguous, and well shared evidences of their existence. Most of the data on exotic mesons in the light quark sector have been collected in the last thirty years with hadronic probes, either in diffractive production with pion beams or anti-proton annihilation on protons and neutrons [10, 11, 12].

The most solid signal appears to be the $\pi_1(1600)$ ($J^{PC} = 1^{-+}$), that has been observed in several decay modes, namely $\eta\pi$, $b_1\pi$, $f_1\pi$, $\rho\pi$, and in several experiments. The signal reported by the E852 Collaboration in the $\pi^- p \rightarrow \pi^- \pi^+ \pi^+ p$ channel [13] is considered the most robust evidence for this state. However, a later analysis of the same channel performed with more statistics and more precise analysis tools [14], as well as negative observations from VES [15] and CLAS [16], raised strong doubts on the existence of this state. The situation is made even more complicated by the recent positive result reported by the COMPASS collaboration [17].

The situation for the other two possible states that have been reported, the $\pi_1(1400)$ and the $\pi_1(2105)$, is even more controversial (see [12] and [11] for a complete review).

To solve this complicate “puzzle” it is necessary to work on three main points. First, an exotic signal to be convincing has to be found in more than one decay mode, since the background that can affect the signal extraction is different, giving different sensitivity to the
signal. Second, exotics need to be searched for in experiments using different probes, since the dominant production mechanisms are still unknown. Finally, precise and robust analysis tools have to be used, since the final results are strictly dependent on their reliability.

A new generation of meson spectroscopy experiments is just started and more will come in the near future, with the ultimate goal of solving the unconventional mesons “puzzle”. Such experiments will collect large datasets of high quality data exploiting different production mechanisms: COMPASS at Cern [18] will use the diffractive production by a 200 GeV pion beam on both proton and nuclear targets, BES-III in Beijing [19] will use $e^-e^+$ annihilation, PANDA at GSI [20] will use proton-antiproton annihilation, and finally GlueX [21] and MesonEx [22] at JLab will use photoproduction on a proton target.

2.1. Amplitude Analysis
The goal of a meson spectroscopy program is to identify resonances measuring their decay products. A resonance is formally described as a pole in the production amplitude with defined angular momentum and isospin.

In practice, resonances are numerous, often broad and overlapping each other: only for a narrow and well-isolated state, like the $\rho$, the resonant structure can be identified by looking at the invariant mass spectrum of the decay products. The identification of a precise state requires the extraction of the corresponding waves from the measured distributions.

This task is performed via the “Partial Wave Analysis” technique (PWA): the cross section of the process is parametrized as a coherent sum of different amplitudes, with defined quantum numbers. The cross section is then fitted to the data to extract amplitudes. Fits can be performed as a function of the invariant mass of the measured decay products and other relevant kinematic variables to derive information on the dependence of the amplitudes on these variables. The PWA is a crucial component for a meson spectroscopy program since the final results are strictly dependent on the reliability of the PWA tools and of the theoretical assumption used in constructing the waves. From the technical side, the improvement in computer science has removed the most part of the limitations that were common in the past. This will allow the analysis of large data sets with adequate number of waves in a reasonable time. From the theoretical side, partial wave analysis can be improved by simplifying the fits introducing known constraints on the amplitudes, and including basic and fundamental properties, such as analiticity and unitarity.

3. Photoproduction of hybrid and exotic mesons
Phenomenological models, like the flux-tube model, indicate that the photon may be more effective in producing exotics hybrids in diffractive production on a proton target than, for example, the pion. The reason for this lies in the fact that the photon spin is one and it can fluctuate into a $qq$ pair with spins aligned. When a $qq$ pair with $\vec{S} = 1$ is excited into a hybrid, the production of exotic quantum numbers is expected to be favored. Phenomenological studies also indicate that exotic mesons can be produced with photon probes with cross sections comparable to ordinary mesons [23, 24]. Finally, the linear polarization of the photons is expected to be a very powerful tool for high precision amplitude analysis, since it can provide information on the production mechanism and acts as a filter for background.

4. Meson Spectroscopy at Jefferson Laboratory
4.1. The Jefferson Laboratory National Accelerator Facility
The Thomas Jefferson National Accelerator Facility (TJNAF or JLab) houses the Continuous Electron Beam Accelerator Facility (CEBAF), a high-current, high-duty electron beam machine with three experimental Halls. A schematic of the accelerator site is shown in figure 2. The CEBAF is composed by two linear accelerators, each adding to the electrons up to 0.4 GeV.
per pass, and two sets of recirculating arcs. The electron beam circulates up to five times in
the accelerator, to reach the maximum energy of about 6 GeV. Three independent beam, with
different energies and currents, can be sent to the three experimental halls. The polarization
of the electron beam can be as high as 85% and it is pseudo-randomly flipped every about 30
ms to reduce systematic effects.

JLab is currently undergoing an upgrade of the accelerator and of the existing experimental
Halls, while a new experimental Hall (Hall D) is being constructed, as shown in figure 3. The
accelerator portion of the upgrade will be constructed on the framework of the existing CEBAF
accelerator. Five new superconducting radio-frequency accelerating elements will be added to
each of the Linacs, and the existing RF cavities will be increased in gradient to achieve a 1.1
GeV/linac accelerating power, and a new recirculating arch will be added to provide an extra
pass through the North Linac. Such new configuration will bring the beam up to 11 GeV for
Halls A, B and C and up to 12 GeV for Hall D.

Figure 2. Aerial view of the JLab accelerator
site.

Figure 3. The JLab accelerator site after the
12 GeV upgrade.

4.2. Meson Spectroscopy Experiments at JLab
Meson Spectroscopy is one of the main topics that will be studied at JLab in the 12 GeV era,
with two dedicated experiments: GlueX in Hall D and MesonEx in Hall B. The scientific goal
of both experiments is to perform a comprehensive measurement of the meson spectrum in the
light quark sector, with precise determination of resonance masses and properties, looking for
rare $q\bar{q}$ states and for unconventional mesons with exotic quantum numbers. Both experiments
will use photon beams with high intensity and linear polarization on a proton target. Final state
particles will be measured with large acceptance detectors: GlueX and CLAS12.

5. The GlueX experiment in Hall D
The GlueX experiment will be held at JLab in the newly-constructed Hall D, with a new
dedicated detector. It will run a meson spectroscopy program using high-energy, linearly
polarized photons on a proton target.
5.1. The GlueX detector

The GlueX detector is based on a solenoid, that is ideal for a fixed-target photoproduction experiment (figure 6). The solenoidal magnetic field traps low energy electromagnetic backgrounds ($e^+e^-$ pairs) generated in the target inside a cone around the beam. It also allows for effective instrumentation of calorimeters to achieve very high acceptance for photons. The superconducting solenoid produces a 2.25 T field. A tagged, high energy, linearly polarized ($\approx 40\%$) Bremsstrahlung photon beam impinges on a 30 cm long liquid-hydrogen target surrounded by a start counter to trigger the DAQ. Moving from the inner to the outer layers of the detector, there is a cylindrical tracking chamber, the CDC, and a cylindrical electromagnetic calorimeter, the BCAL. Downstream of the CDC are four sets of circular planar drift chambers, FDC, followed by a time-of-flight wall, TOF. This is followed by a circular planar electromagnetic calorimeter, the FCAL. Some space has been reserved between the downstream end of the magnet and the TOF for a possible particle identification (PID) system. This design provides for nearly $4\pi$ acceptance for both charged particles and photons. While the acceptance is not completely uniform in all variables, there are no holes in the kinematic variables of interest.

5.2. The GlueX photon beam

The GlueX experiment requires a photon beam with energies in the range 8-9 GeV, high linear polarization and high intensity (up to $10^9 \gamma/s$), that has to be obtained from the primary electron beam delivered by the CEBAF accelerator. The method used to produce such a beam is coherent Bremsstrahlung in a oriented crystal. 12 GeV electrons from the accelerator pass through a thin diamond radiator (20 µm), generating an intense beam of high-energy photons with a continuous energy spectrum dominated by a single peak: figure 7 shows the typical Bremsstrahlung spectrum calculated for a diamond crystal radiator of 20 µm and a 1 µA electron beam of 12 GeV. A significant fraction of the total power in the beam is concentrated inside the peak. Using electrons with energy $E_0$ the peak position can be varied, from 0 to 90% $E_0$ simply rotating the crystal.

The photon spectrum inside the peak has a large degree of linear polarization: figure 8 shows the linear polarization of the photons in the peak as a function of the energy of the electron beam. The entire beam polarization appears in the coherent peak, while the continuous background only dilutes it. To get maximum polarization it is crucial to separate the two contributions and take
Figure 6. Different subsystems of the GlueX detector. In orange, the charged particle tracking subsystem. In blue, the calorimetry subsystem. In green, the particle identification subsystem. See text for the description of the different subdetectors.

Figure 7. Bremsstrahlung spectrum for a diamond crystal radiator of 20µm and a 1 µA electron beam of 12 GeV. The coherent peak is clearly visible. The red line represents the contribution of the incoherent Bremsstrahlung. Figure is taken from [25].

only photons inside the peak. This can be done using a suitable collimator, exploiting the fact that the two components have angular distributions with different characteristics. Collimating away all photons beyond some angle \( \theta \), the incoherent spectrum is attenuated uniformly at all energies, while the coherent spectrum under the relevant peak is left unchanged from the maximum energy down to a certain cut-off.

The precise energy of each produced photon is determined measuring the momentum of the corresponding recoil electron in a dedicate, Elbek-type tagging spectrometer, schematically shown in figure 9.

The primary 12 GeV electrons from the CEBAF accelerator hit the diamond radiator, where a small fraction of them emits Bremsstrahlung photons. Then the electrons enter in a quadrupole
and in the dipole field region, to be bended by the tagger magnet. Electrons that did not go under Bremsstrahlung are deflected by 13.4° going straight toward the beam dump. The others are deflected more, depending on the energy they lost in the radiator, entering in the active detector region, immediately after the focal plane in figure 9.

The spectrometer is made by two detectors: a set of 190 fixed scintillator counters spanning the electron momentum range from 3.0 to 11.7 GeV and a movable “microscope” of 500 scintillating fibers. With the fixed array it is possible to measure the full tagged photon spectrum, with energy resolution of 0.25 % and reduced rate. The movable “microscope” is used whenever a better resolution or a highest rate is required.

5.3. Expected performances and results

The reaction $\gamma p \rightarrow 3\pi n$ involving three charged pions in the final state has been used as a benchmark to test the potential of the GlueX detector and tools developed for the analysis. The reason why this reaction has been chosen is that it has been studied by past experiments, like E852 [13] and VES [15], with controversial results about the presence of the exotic $\pi_1(1680)$ state. A further investigation of this final state is therefore highly desirable.

The test procedure was the following: pseudo Monte-Carlo data have been generated using information from E852 as input, including the exotic $\pi_1(1600)$, simulating the statistic corresponding to 3.5 hours of beamtime in nominal operating conditions. Then this set of data
was passed through the Monte-Carlo code of the detector to simulate its response. Finally, an amplitude analysis based on a isobar model was performed, dividing the 3π invariant mass range in independent, 20 MeV width, bins.

The intensity for this reaction, having a photon beam along the z axis with fractional linear polarization f and including n different resonances X_β is written as follows:

\[ I = \sum_{p=\pm 1} \frac{1 + pf}{4} \left| \sum_{\beta=1}^n V_{p,\beta}(< X_\beta | R > + pe^{2i\alpha} < X_\beta | L >) \right|^2 \]  

(1)

where |R> and |L> are the photon helicity basis states and α is the angle between the production plane of the resonance X and the plane of polarization of the photon beam. V_{p,\beta} is the production amplitude for the resonance X_β, that is replaced by a free parameter in the maximum likelihood fit involved in the partial wave analysis. Finally, p = +1 represents photon polarization along x and p = −1 represents photon polarization along y.

Table 1 reports the resonances included in the analysis.

| Resonance | Decay channel | Relative angular momentum L |
|-----------|---------------|----------------------------|
| a_1(1230) | ρ π           | S                          |
| a_2(1320) | ρ π           | D                          |
| π_2(1670) | f_2 π         | S                          |
| π_2(1670) | ρ π           | P                          |
| π_1(1600) | ρ π           | P                          |

Table 1. Resonances included in the 3π final state analysis.

Results are reported in figure 10. The signal from the π_1(1600) is clearly visible, even if it corresponds only to 1.5% of the overall intensity. This demonstrates that the GlueX detector can be effectively used to perform a comprehensive partial wave analysis and find exotic signals.

6. The MesonEx experiment in Hall B

MesonEx (JLab Exp-11-005) is an experimental program that will study meson spectroscopy through quasi-real photoproduction. It will take place in the Hall B of Jefferson Laboratory, using the CLAS12 detector [27] and a new Forward Tagger facility (FT). The goal of this experiment is to perform a comprehensive study of the meson spectrum in the light quark sector, in the energy range of few GeVs, with precise determination of resonance masses and properties.

6.1. Quasi-real photoproduction

During the 6 GeV operations, photoproduction experiments were run in Hall-B making use of the CLAS detector [26] for the produced hadrons and a Bremsstrahlung tagger facility to produce and tag real photons in the energy range between 1 GeV to 5.5 GeV. This setup cannot be operated at 11 GeV because of the limited bending power of the existing magnet.

In the MesonEx experiment, quasi-real photons on an hydrogen target will be used. Photons are produced by the 11 GeV electron beam from the CEBAF accelerator scattering at very low angle (2.5°-4.5°) from the target, with Q^2 values of about 10^{-1} GeV^2 or lower.

In the unpolarized electron scattering process (one-photon exchange approximation), the virtual photon transverse polarization is:

\[ \varepsilon = \left[ 1 + 2\frac{Q^2 + \nu^2}{Q^2} \tan^2(\theta_{\nu}/2) \right]^{-1} \]  

(2)
Figure 10. Result of the GlueX partial wave analysis of the $3\pi$ final state. The black curve reports the overall intensity for the reaction, while the colored points report the intensities of the 5 different waves for each $3\pi$ invariant mass bin.

Figure 11. Isobar model for the reaction $\gamma p \rightarrow 3\pi n$. $X$ is the produced resonance, that then decays into isobar $I$ and a "spectator" pion. $I$ in turn decays into 2 pions.

where $\nu$ is the photon energy and $\theta_{e^{'}}$ the electron scattering angle. The longitudinal polarization is given by $\varepsilon_L = \frac{Q^2}{\nu^2} \varepsilon$ [28]: at very low values of $Q^2$ the virtual photon beam becomes, for all practical purposes, almost a real photon beam, since $\varepsilon_L \approx 0$.

Using the above relations the photon polarization will be determined event by event, simply measuring the electron three-momentum. The polarization plane coincides with the electron scattering plane and the degree of polarization mainly depends on the energy: the associated systematic uncertainty is only affected by the electron detection resolution.

In the MesonEx experiment the CLAS12 detector will be used to detect hadrons in the final state. However, its geometrical acceptance prevents to detect electrons at low angles: it is therefore necessary to add a new component, the Forward Tagger, to measure electrons scattered below $5^\circ$ and thus to reconstruct kinematic variables of the quasi-real photons.

6.2. The CLAS12 detector
As part of the 12-GeV upgrade of the CEBAF accelerator complex at Jefferson Lab, the existing CLAS detector in Hall B will be upgraded to CLAS12. This detector is designed to perform experiments using high energy electron beam impinging on polarized and unpolarized targets at luminosities up to $L = 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$. CLAS12 consists of two parts, a forward detector (FD) and a central detector (CD), respectively shown in figure 12 and 13.

The Forward Detector will detect and identify charged and neutral particles scattered between $5^\circ$ and $40^\circ$, in the full momentum range. Particles will be detected in six identical magnetic spectrometers based on six coils, superconducting toroidal magnet. Each spectrometer will be equipped with a Forward Vertex Tracker (FVT), high threshold Cherenkov Counter (HTCC),
a set of Drift Chambers (FDC), low threshold Cherenkov Counter (LTCC), time-of-flight scintillator counters (FTOF), and electromagnetic calorimeters (FEC).

The Central Detector is meant to measure charged hadrons and neutrons in the angular range from 35° to 125° and momenta lower than 1.5 GeV/c. Charged particles will be detected by two barrel shaped detectors, Si-tracker (BST) and time-of-flight counters (CTOF). Both detectors are positioned inside a solenoidal magnet and cover the full azimuthal angular range. Neutrons will be detected by a dedicated detector (CND) positioned between CTOF and the cryostat of the solenoid.

6.3. The Forward Tagger detector
The angular range of interest for scattered electron detection in the MesonEx experiment is between 2.5° and 4.5°, corresponding to a $Q^2$ range between 0.01 GeV$^2$ and 0.3 GeV$^2$. This angular range is outside the CLAS12 acceptance, therefore a new dedicated detector, the Forward Tagger, has to be added to the experimental setup.

To reconstruct the quasi-real photon variables it is necessary to measure the scattered electron three momentum. The most relevant quantities are its energy $E_{e'}$, its polar angle $\varphi_{e'}$, and its azimuthal angle $\theta_{e'}$. From them it is possible to reconstruct the quasi-real photon energy $\nu$, the $Q^2$, the polarization $\varepsilon$, and the polarization plane, that coincides with the electron scattering plane.

The Forward Tagger will be made of a calorimeter (FT-Cal), to identify the electron, measure its energy, and provide a fast trigger signal, a tracker (FT-Trck), to measure the scattering angles, and a scintillation counter (FT-Hodo) to provide $e/\gamma$ separation. The Forward Tagger will be placed between the high threshold Cherenkov Counter (HTCC) and the torus support, at about 190 cm downstream of the target (nominal) position.

The FT-Cal is the core of the Forward Tagger. It has to fulfill strong requirements in terms of radiation hardness, light yield, radiation length, recovery time, energy and time resolution. Due to the limited space available and its position inside CLAS12 it has to be compact and operable in a high magnetic field environment.
The choice that has been done in the MesonEx experiment is to construct a calorimeter based on PbWO$_4$ scintillating crystals. In the recent years this material has been extensively studied and shown to be very resistant to radiation damage. PbWO$_4$ crystals has been used in large scale detectors, such as CMS-ECal[29], ALICE-PHOS [30], PANDA-EMC [31] and CLAS-IC [32]. PbWO$_4$ has a very fast scintillation decay time (6.5 ns), a very small radiation lenth (0.9 cm), and a small Moliere radius (2.1 cm). Even if the light yield is only 0.3% of NaI(Tl) the designed energy resolution of the overall calorimeter is of $2%/\sqrt{E(GeV)} \oplus 1\%$.

Due to the expected high range from electromagnetic background, the calorimeter will be highly segmented in the transverse direction to maintain each channel at a sustainable readout-rate. The size of each crystal will be $1.5 \times 1.5 \, cm^2$, comparable with the characteristic transverse size of the electromagnetic shower to contain the signal induced by incident electrons to few crystals.

The crystal size is also well matched to the photodetectors. For each crystal the light will be read-out by an Avalanche Photo Diode (APD Hamamatsu S8664-1010), with active area of $10 \times 10 \, mm^2$. This design has been shown to meet the required criteria in terms of radiation hardness and operability in a magnetic field.

6.4. Expected performances and results

The reaction $\gamma p \rightarrow 3\pi n$, involving three charged pions in the final state, has also be used as a benchmark reaction to study the performances of the MesonEx experimental setup and the analysis tools to perform the Partial Wave Analysis. As already described for GlueX, it is also a reaction with large physical interest due to the contradictory results about the $\pi_1(1600)$ reported by different past experiments in this channel.

This reaction can be easily accessed in CLAS12 by detecting the three charged pions in the forward part of the CLAS12 Detector. The exclusivity of the reaction is ensured by using the Forward Tagger to determine the 3-momentum of the initial state photon and then applying the missing mass technique to select events with a missing neutron.

The experimental acceptance for this channel has been evaluated generating events according to the Isobar model with a flat $3\pi$ invariant mass and exponential $t$ channel distribution, $\frac{d\sigma}{dt} \propto e^{-5|t|}$. The response of CLAS12 and FT was then analyzed performing a full simulation of the detector.

The most important kinematic variables for this reaction, that the production amplitude may depend from, are the invariant mass of the $3\pi$ system, the momentum transfer $t$ and the polar angles of the isobar in the meson resonance decay, as measured in the Gottfried-Jackson (GJ) frame. Figure 14 shows the acceptance for these kinematics variables, for a magnetic field configuration corresponding to half of the nominal value. This configuration has been chosen due to the higher acceptance at low $M_{3\pi}$ (approximately a factor 5 at 1.4 GeV/$c^2$ respect to the nominal field configuration).

The suitability of the MesonEx experimental setup and analysis tools for Partial Wave Analysis has been tested as follows. First a set of pseudo Monte-Carlo data have been generated according to a specifically-designed model for the $3\pi$ production [22]. The model defines 8 possible final states, summarized in table 2, decaying to $\pi^+\pi^+\pi^-$, with an additional recoiling neutron in the final state. An exotic $\pi_1(1600)$ state is included, with a contribution of 2% to the overall intensity. One million of events have been generated, divided into two $t$ bins at -0.2 and -0.5 GeV/$c^2$, each with the same number of events.

These events were then tracked through the detector via a MonteCarlo code, and only those with 3 reconstructed pions were accepted for the PWA. Finally, maximum likelihood fits were performed independently in each $3\pi$ invariant mass bin to extract production amplitudes.

Figure 15 shows the comparison between the generated waves and the result of the fits for each $t$ bin. The generated waves are reproduced very well for all channels, including the $\pi_1$ exotic. Even if its contribution is just 2% of the total intensity, a clear, statistically significant
signal is reproduced. This leads to the conclusion that the CLAS12-Forward Tagger system is intrinsically capable of meson spectroscopy measurements via Partial Wave Analysis.

**Table 2.** The meson states produced in the model of $\pi^+\pi^+\pi^−$ production, detailed in [22]. $L$ is the relative orbital angular momentum between the isobar and the bachelor pion.

| State   | $J^{PC}$ | L  | Decay Mode |
|---------|----------|----|------------|
| $a_1$ (1260) | 1++     | D  | $\rho\pi$  |
| $a_2$ (1320) | 2++     | D  | $\rho\pi$  |
| $\pi_2$ (1670) | 2−+     | P  | $\rho\pi$  |
| $\pi_2$ (1670) | 2−+     | F  | $\rho\pi$  |
| $\pi_2$ (1670) | 2−+     | S  | $f_2\pi$   |
| $\pi_2$ (1670) | 2−+     | D  | $f_2\pi$   |
| $\pi_1$ (1600) | 1−+     | P  | $\rho\pi$  |

**7. Conclusions**

Meson Spectroscopy is a powerful tool to answer to fundamental questions in QCD, as the origin of color confinement and the role of gluons inside hadrons. Mesons are the simples quark bound
Figure 15. The intensities of the 8 different isobar channels in the $3\pi$ model, see table 2. The bottom right plot shows the total intensity. The black line shows the generated waves, while the blue and red points are the fit results for $t = 0.2$ and $0.5 \,(GeV/c)^2$, respectively.

system, and therefore the ideal "laboratory" to study the strong force at the non-perturbative energy scale of few GeVs. In particular, unconventional mesons (i.e. states incompatible with a simple $q\bar{q}$ structure) would be the best experimental evidence of the active role of gluons in hadron dynamics.

A new generation of high precision meson spectroscopy experiments is starting in the near future with the ultimate goal of solving the unconventional mesons "puzzle", that has been delineated by the controversial results reported by past measurements. Jefferson Laboratory will play an active role in this program during the 12 GeV era, with two dedicated experiments: GlueX in Hall D and MesonEx in Hall B. They will be installed inside the experimental halls during 2014, to be ready for data taking in 2015.

The goal of these experiments is to use photo-production on a proton target to investigate the meson spectrum in the energy range of few GeVs, looking for rare $q\bar{q}$ and exotic states: Partial Wave Analysis technique will be used to determine their mass and properties.

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