MESON SPECTROSCOPY AT CLAS12*

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Meson, being the simplest hadronic bound system, is the ideal "laboratory" to study the interaction between quarks, to 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. With the imminent advent of the 12 GeV upgrade of the Jefferson Lab, a new generation of meson spectroscopy experiments will start. The "Meson-Ex" experiment in Hall B will use quasi-real photo-production to explore the spectrum of mesons in the light-quark sector, in the energy range of few GeVs.

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1. Introduction

The phenomenology of hadrons 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

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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 [2–4] and lattice QCD calculations [5] 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 was 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.

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.

2. 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, 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.

3. Photoproduction of hybrid and exotic mesons

Phenomenological models, such as 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 $q\bar{q}$ pair with spins aligned. When a $q\bar{q}$ 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 [6, 7].

4. The MesonEx experiment in Hall B at the Jefferson Laboratory

MesonEx (JLab Exp-11-005) [8] is an experimental program that will study meson spectroscopy trough quasi-real photoproduction. It will take place in the Hall B of the Jefferson Laboratory, using the CLAS12 detector [9] and a new Forward Tagger facility (FT) [10]. 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.

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, Fig. 1. CEBAF is composed with 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.

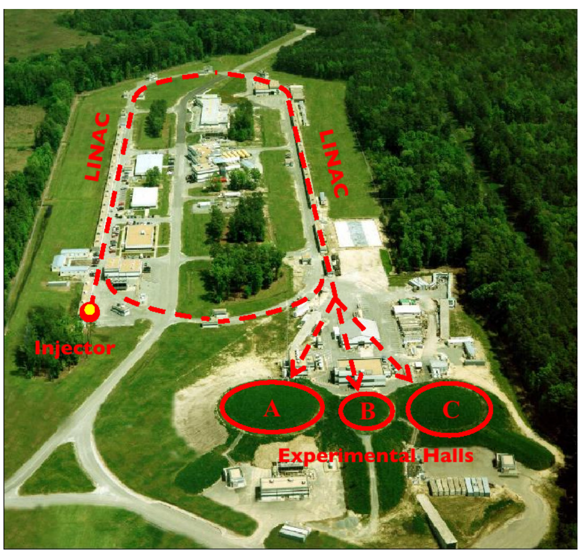

Fig. 1. Aerial view of the JLab accelerator site.

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. 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, 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, see Fig. 2.

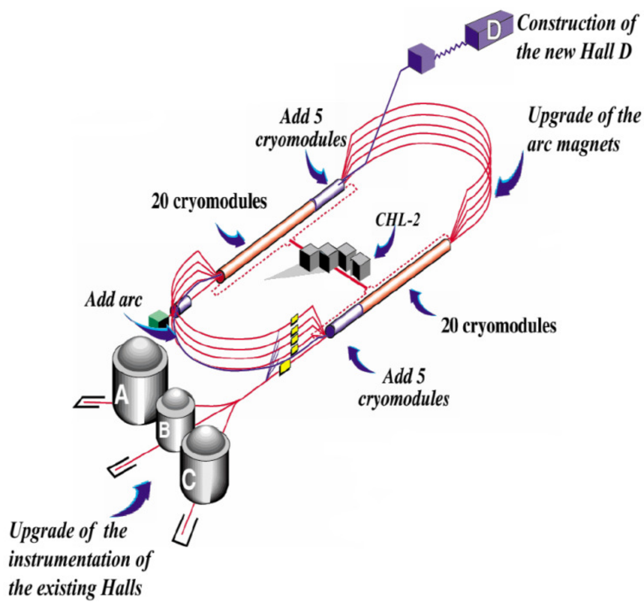

Fig. 2. The JLab accelerator site after the 12 GeV upgrade.

4.2. Quasi-real photoproduction

The experimental technique employed in MesonEx is the electron scattering at low angle on a liquid hydrogen target. In the unpolarized electron scattering process (one-photon exchange approximation), the virtual photon *transverse* polarization is

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

where ν is the photon energy and $\theta_{e'}$ the electron scattering angle. The *longitudinal* polarization is given by $\varepsilon_{\mathrm{L}} = \frac{Q^2}{\nu^2}\varepsilon$ [11]: at very low values of Q^2 the virtual photon beam becomes, for all practical purposes, almost a real photon beam, since $\varepsilon_{\mathrm{L}} \simeq 0$.

5. Expected performances and results

The reaction $\gamma p \to 3\pi n$, involving three charged pions in the final state, has been used as a benchmark reaction to study the performances of the MesonEx experimental setup and the analysis tools to perform the Partial Wave Analysis. Such reaction has a large physical interest due to the contradictory results about the presence of an exotic meson, the $\pi_1(1600)$, reported by different past experiments in this channel.

This reaction can be accessed in MesonEx 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 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 3π production [8]. The model defines 8 possible final states, summarized in Table I, decaying to $\pi^+\pi^+\pi^-$, with an additional recoiling neutron in the final state. An exotic 1^{-+} $\pi_1(1600)$ state is included, with a contribution of 2% to the overall intensity. One million of events have been generated, equally distributed in two t bins at -0.2 and -0.5 GeV^2.

These events were then projected on the detector trough a MonteCarlo code, and only those with 3 reconstructed pions were accepted for the PWA. Finally, maximum likehood fits were performed independently in each 3π invariant mass bin to extract production amplitudes.

TABLE I

The meson states included for the $\pi^+\pi^+\pi^-$ production, detailed in [8]. L is the relative 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	$\rho\pi$

Figure 3 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 π_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.

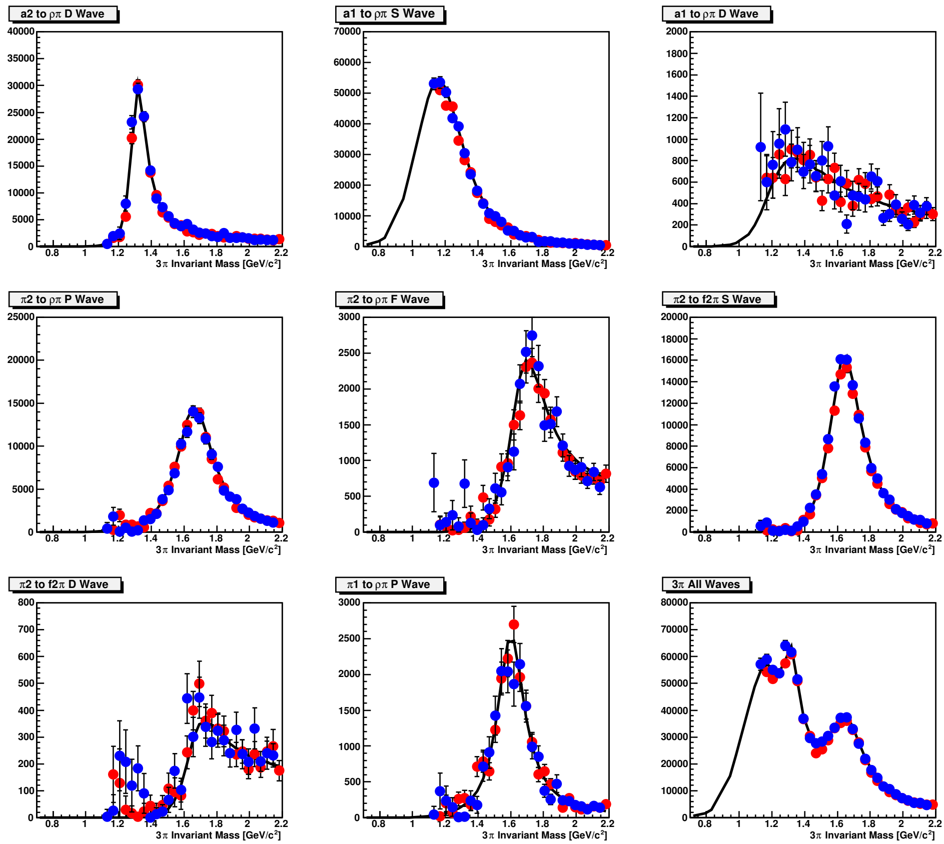

Fig. 3. The intensities of the 8 different isobar channels in the 3π model, see Table I. The bottom right plot shows the total intensity. The black line shows the generated waves, while the light gray/blue and dark gray/red points are the fit results for $t = 0.2$ and 0.5 $(\mathrm{GeV}/c)^2$.

6. 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 system and, therefore, the ideal "laboratory" to study the strong force at the non-perturbative energy scale of few GeVs. In particular, unconventional mesons would be the best experimental evidence of the active role of gluons in hadron dynamics.

The MesonEx experiment in Hall B at the Jefferson Laboratory will use quasi-real 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. MesonEx will be installed inside the experimental hall during 2014, to be ready for data taking in 2015.

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