The hybrid mesons quest: the MesonEx experiment at Jefferson Laboratory

Alessandro Rizzo[1] for the CLAS Collaboration

[1] The University of Rome "Tor Vergata" and INFN Roma2, Via della Ricerca Scientifica 1, 00133 Roma, Italy

E-mail: `alessandro.rizzo@roma2.infn.it`

Abstract. The meson spectroscopy plays nowadays a central role in the investigation of hadron structure thanks to the possible existence of exotic hybrid mesons, *quark-antiquark-gluon* bound states. Their explicit gluonic degrees of freedom which should clearly emerge from a Partial Wave Analysis (PWA) of the corresponding Dalitz plot of the exotic particle decay, may result in final J^{PC} configurations not allowed in the constituent quark model. Besides this clear signature, hybrid mesons are also expected to have a large particle multiplicity decays, requiring for their search an experimental apparatus with high performances in terms of rate capability, resolution and almost a full acceptance to apply PWA methods. New-generation experiments are planned at Thomas Jefferson National Laboratory (VA, USA) for which an unprecedented statistics of large multiplicity decay events with fully reconstructed kinematics will be available. In particular for the MesonEx (CLAS12) experiment in Hall B, a wide scientific program that will start in 2016 has been deployed to study the meson spectrum at energies up to 11 GeV. A key role in such program is played by the Forward Tagger apparatus of the experiment, which will allow to extend the study of meson electro-production to very low Q^2 values, in a quasi-real photo production kinematical region, where the production of hybrid mesons is expected to be favorite. Currently a new analysis framework for the search of the hybrid mesons is being set up by the HASPECT network, an international structure which gather people involved into theoretical and experimental hadronic physics all over the world. The goals of the network is to develop new analysis models and statistical techniques to unfold the signal and background distributions in high-statistics datasets. In this work are briefly presented the first preliminary results from the application of a statistical technique, namely the sPlot, to the data already acquired by the CLAS experiment for the decay $f_1(1285) \rightarrow (\eta)\pi^+\pi^-$.

1. The meson spectrum and the exotic hybrid configuration

The meson spectrum may carry fundamental information about the gluonic contribution in the hadron structure, thanks to the possible existence of states $q\bar{q}g$, exotic meson configurations not predicted by the *Gell-mann* model. These hybrid states are characterized by J^{PC} configurations not allowed for standard $q\bar{q}$ states[1], that may be experimentally investigated through Partial Wave Analysis (PWA) of the experimental data.

Several theoretical models include gluonic excitations contribution within different frameworks [1–3]: in this work the attention is focused on the Flux-tube model [4]. The gluonic flux tubes are

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[1] J, P and C are the quantum numbers related to the total spin, the parity and the charge conjugation respectively, which univocally characterize the bound state.

a consequence of the non-abelianity of Quantum Chromo-Dynamics (QCD) theory, which, differently from Quantum Electro-Dynamics (QED), allows the gauge bosons (the gluons) to interact among each other, forming flux tubes which bind the interacting quarks. In this model, standard meson configurations correspond to a ground state flux tube which links the *quark-antiquark* pair, resulting in a J^{PC} configuration already predicted by the *Constituent Quark Model*. Considering the first excited states of the flux tube ($J^{PC} = 1^{+-}$ or $J^{PC} = 1^{-+}$) and arranging them with *pseudo-scalar* ($L = 0$, $s = 0$, $J = 0$) or *vector* ($L = 0$, $s = 1$, $J = 1$) mesons J^{PC} configurations, it is possible to form exotic hybrid configurations $J^{PC} = 0^{--}, 1^{-+}, 0^{+-}, 2^{+-}$, not predicted by the Gell-mann model and hybrid configurations $J^{PC} = 0^{++}, 1^{--}, 1^{++}, (0, 2)^{-+}, 1^{+-}$, already predicted by the Gell-mann model.

The flux-tube picture well explains also the hadronization process and the high particle multiplicity states in which a hybrid meson is supposed to decay in. A flux-tube binds two interacting quarks with a force of the form $\vec{F} = -k\vec{x}$, where k is a constant which is proportional to the strength of the interaction and $\vec{x}$ is the distance between the two quarks. The binding potential $V = -\frac{1}{2}kx^2$ grows rapidly with $|\vec{x}|$, till it reaches the energy of the mass of a quark pair. A this point the breaking of the flux-tube may occur with the formation of at least two new mesons in which the mother particle decays in.

In this picture the hybrid mesons are supposed to decay in high-particle multiplicity events because the flux-tube binding the quarks is in an excited state, a condition that enhances the energy available to form couples of new mesons.

2. Exotic hybrid mesons: hints and experimental evidences

Hints about the existence of such hybrid states come from Lattice QCD (LQCD) with unquenched calculations, that in these last years is approaching a pion mass considerably close to the physical one. The good predictive power of LQCD, due to the good agreement of lattice calculations and the experimental data for the meson spectrum in terms of number of states and mass hierarchy, makes the LQCD predictions about the existence of exotic hybrid mesons one of the pillars of the hybrid exotic mesons theory. In particular, according to these calculations, the lowest lying hybrid meson surprisingly presents the configuration $J^{PC} = 1^{-+}$ with a mass of about 1.6 GeV, followed by the configuration 0^{+-} with a mass of about 2 GeV: both states are lying in an energy range fully accessible to the CLAS12 experiment at Jefferson Laboratory. The experimental history about evidences of such hybrid states starts in the 80's, when a joint CERN-IHEP experiment (GAMS group [5]) claimed for a possible existence of hybrid state $J^{PC} = 1^{-+}$: in the analysis of the channel $\pi^- p \rightarrow \pi^0 \eta n$, a p-wave contribution of the $\eta\pi$ bound state (namely $\pi_1(1400)$) was supposed to exist to better explain the behavior of the experimental data. To confirm that claim, the experiment E852 at the Brookhaven National Laboratory [6] started a series of systematic studies of the same channel and the crossed-charged one ($\pi^- p \rightarrow \pi^- \eta p$) at 18 GeV, observing the lower lying hybrid state. Also the experiments Crystal Barrel [7] and VES [8] confirmed such observations, by studying the channels $n\bar{p} \rightarrow \pi^- \pi^0 \eta$, $p\bar{p} \rightarrow \pi^0 \pi^0 \eta$ and $\pi^- N \rightarrow \pi^- \eta N$ respectively.

Another possible candidate for the lowest lying hybrid state $J^{PC} = 1^{-+}$ is the $\pi_1(1600)$, whose experimental evidence has been more controversial. The E851 experiment at Brookhaven National Laboratory claimed for the existence of such excited state [9] analyzing a dataset of 250k $\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$ events at 100 GeV. In a following re-analysis of a higher statistical sample the previous claim was not confirmed by the same collaboration [10], but recently the hybrid $\pi_1(1600)$ has been observed with high statistics by the COMPASS experiment in the $\pi Pb \rightarrow \pi\pi\pi Pb$ channel [11].

3. The CLAS12 apparatus at the CEBAF accelerator: the meson spectroscopy program and the experimental investigation of hybrid mesons

The experimental investigation of hybrid mesons will be one of the main tasks of the spectroscopy program deployed for the MesonEx (or CLAS12) experiment, located at the experimental Hall B of the *Thomas Jefferson National Laboratory* (Virginia, USA). The recent upgrade of the Continuos Electron Beam Accelerator Facility (CEBAF) to 12 GeV [12] will allow MesonEx to investigate the mass range where the exotic states are supposed to lie. The accelerator is based on the Superconductive Radio-Frequency technology with two linacs, made of 25 cryo-modules each, placed between two sets of ricirculating arcs: such configuration enhances the energy of the accelerated electron beam by 1.2 GeV at each round-pass. When the beam reaches an energy of 11 GeV (5th pass) it is extracted to the Hall B, toward CLAS12 apparatus, with a maximum delivered current of 200 μA.

MesonEx (CLAS12) is the new experimental apparatus, a spectrometer, specifically designed for the upgraded CEBAF electron beam [13], that is replacing the former CLAS experiment, which took data till 2012 at energies up to 6 GeV. The geometry of the new apparatus ensures an acceptance which is close to 4π and a good hermeticity: it is divided into 6 sectors corresponding to 6 different azimuthal regions, and it covers both the regions around the target (Central Detector region) and the forward direction region (Forward Detector region). The magnetic field, which is used to measure the particle momenta, is generated by a superconductive solenoid magnet (5 T) in the Central Detector and by a superconductive torus magnet (3.6 T) in the Forward Detector. The different detectors of the experimental apparatus are described in detail in [13] and schematically in [14].

The CLAS12 experiment will look for exotic-hybrid mesons produced in quasi-real photoproduction reactions induced by the electron-beam from CEBAF impinging on nuclear target (LH_2) placed in the Central Detector region. The production of exotic hybrid mesons is expected indeed to be favored using a photon beam rather than a meson beam (K or π), because of the different final J^{PC} configurations accessible by a $J = 1$ probe (the photon) interacting with a nucleon. Recalling the considerations exposed in Section 1 we may see that arranging the first excited states of the flux tube ($J^{PC} = 1^{+-}$ or $J^{PC} = 1^{-+}$) with the J^{PC} configurations of vector mesons gives more exotic hybrid configurations ($J^{PC} = 1^{-+}, 0^{-+}, 2^{-+}$) than the one obtained by taking the pseudo-scalar mesons configurations ($J^{PC} = 0^{--}$). Moreover it is possible to obtain the lowest lying exotic hybrid states ($J^{PC} = 1^{-+}, 0^{-+}$) only considering the vector mesons quantum numbers: in the case of photoproduction the quantum number of the vector mesons ($J = 1$) is brought by the photon, so we expect such channel to be more favorably interested by the exotic-hybrid mesons production than the production via K or π beams ($J = 0$).

4. MesonEx and photoproduction reactions in Hall B

The Hall B at Jefferson Laboratory, where the CLAS12 (and previously CLAS) is located, has a longstanding experience about photoproduction reactions and experimental techniques used to obtain a photon beam from an electron one. During the 6 GeV era, for the CLAS experiment, the bremsstrahlung emission was used to produce a tagged real γ-ray beam [16]. In this technique the electron beam from CEBAF impinges on a thin diamond radiator, producing linear polarized photons via coherent bremsstrahlung emission: the electron and the produced photon beams are then separated by passing through a dipole which bends the electrons towards a scintillating *hodoscope*. Thanks to the energy conservation relation it is possible to associate the correct energy to the interacting photon in the nuclear target (E_γ) according to the formula $E_\gamma = E_e - E_{e'}$, where $E_{e'}$ is the energy of the deflected electron measured by the hodoscope and E_e is the electron beam energy. Nowadays this technique is used to produce the photon beam for the GlueX experiment in Hall D at Jefferson Laboratory, which, as the CLAS12 experiment, has an important meson spectroscopy program.

In the 12 GeV era a different technique will be used for the CLAS12 experiment to study photo-induced reactions: the quasi-real photoproduction. Such technique is quite well established in higher energy physics experiments like HERMES, BABAR [17] and COMPASS [11], and it will be used in Hall B to search for the hybrid meson states with a complementary approach to the GluEx experiment. The quasi-real photoproduction technique takes place in the electro-production regime: when the electron beam impinges on the nuclear target, the electrons are scattered by an angle θ. Events with a small θ are the ones where the exchanged photon between the probe and the nucleon of the target has a low Q^2 or, in other words, the γ is quasi- on mass shell. Such events are those of quasi-real photoproduction.

In CLAS12 experiments the electrons, scattered at small θ angles, are detected by the Forward Tagger (FT), an apparatus placed immediately after the nuclear target (between the Central and the Forward Detector region, see Section 3), covering the polar angle range from 2.5 to 4.4 degrees. The FT apparatus is composed by a tracker, based on Micromegas technology, to measure the angle θ and the polarization plane of electrons; a scintillation hodoscope, used as a veto for gammas, and an electromagnetic calorimeter made of $PbWO_4$ crystals, to measure the scattered electrons energy. In a photoproduction event, tagged by the Forward Tagger, the multi-particle hadronic decay is detected by the CLAS12 apparatus, which provides a high rate capability, almost a 4π acceptance and excellent Particle IDentification (PID). Quasi-real photons will have an energy spectrum between 6.5 and 10.5 GeV, a linear polarization degree that can be up to the 70% of the electron beam one and a high luminosity, of the order of 10^{35} $cm^{-2}s^1$ (considering 5 cm long LH_2 target).

5. Establishing a new analysis framework to search for exotic hybrid mesons: the case of $f_1(1285)$ meson decay

The exotic hybrid mesons are expected to have a clear signature in a Partial Wave Analysis (PWA) of the experimental data, thanks to their *unconventional* J^{PC} configuration. The PWA is a powerful tool to search for this new physics but it requires several features to obtain reliable results, in particular high statistics, an almost full-acceptance of the experiment used to collect the data and a strong background rejection. In order to be ready for the first data-taking of the CLAS12 experiment in 2017, an international collaboration, namely HASPECT (HAdron SPEctroscopy CenTer), is currently working to set up a new analysis framework to search for new physics, in particular the lowest lying exotic hybrid mesons. During these years the collaboration studied if the CLAS12 experimental features will fulfill the requirements to successfully look for such states and, at the same time, developed new analysis tools. The excellent performances in terms of rate capability expected for the CLAS12 apparatus will fulfill the high-statistics requirements, while the apparatus acceptance and its influence on a possible PWA has been investigated with two complementary approaches. A first feasibility test has been done using simulated data for the $\gamma p \to \pi^+\pi^+\pi^- n$ channel where the sum of 8 isobar channels has been considered to describe resonances in S, P, D and F waves decaying into $\rho\pi$ or $f_2(1270)$. In this data an exotic contribution in the P wave has been injected to simulate the hybrid $\pi_1(1600)$ decaying in ρp, with a cross section of 200 nb. After folding the events with the MesonEx acceptance and processing them through the full reconstruction chain, the data have been fitted using a proper partial wave set in the framework of the isobar model, in selected bins of transferred momentum t. All known resonances, $a_2(1320)$ (D-wave), $a_1(1260)$ (D-wave), $\pi_2(1670)$ in the two decay channels ρp (P and F wave) and $f_2(1270\pi)$ (S and D wave), have been correctly reproduced at the right mass values, as well as the additional exotic signal. The second feasibility study is based on data already acquired by the CLAS experiment at 6 GeV. By studying the $\gamma p \to \pi^+\pi^-\pi^0 p$ benchmark reaction for the ω decay in three pions, the result has been projected on the CLAS12 acceptance and fitted. In this case it has been observed that the result is stable against the acceptance corrections, demonstrating that the PWA will

be feasible for the CLAS12 experiment.

The analysis of the decays of $f_1(1285)$ meson in the $(\eta)\pi^+\pi^-$ channel, concerns the development and the application of new analysis tools to reject the background. Using data already acquired by the CLAS experiment during the g11 run, in which a real photon beam was used to photo-produce the mesons, an analysis tools based on the sPlot method [19, 20] has been developed and tested on the Dalitz Plot of the decay (fig. 1). The sPlot [19] is a statistical method based
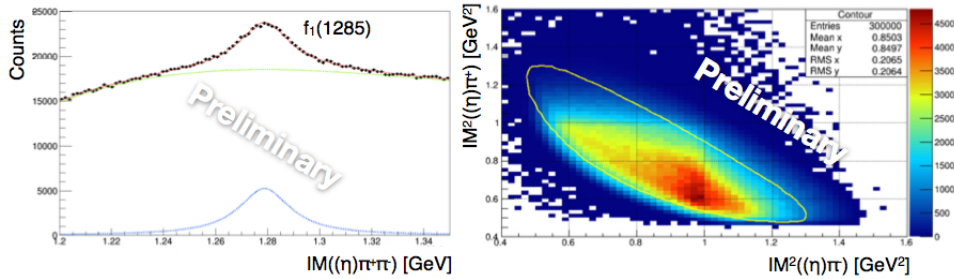
Figure 1: Left Panel: The invariant mass spectrum of the $(\eta)\pi^+\pi^-$ mesons and the PDFs used for the fit. In blue the Breit-Wigner function used to modeling the $f_1(1285)$ signal, in green the 4th grade Chebychev polynomial function used for the background and in red the sum of the two functions. Right Panel: Dalitz plot for the $f_1(1285)$ decay in terms of invariant mass square for the couples of mesons $(\eta)\pi^+$ versus $(\eta)\pi^-$. The yellow line is the theoretical Dalitz boundary.

on the maximum likelihood fit used to calculate a weight (namely the sWeight) for each decay event: the weight will have a different numerical value if the considered event is more likely background ($-1 < sWeight < 0$) or signal ($0 < sWeight < 1$).
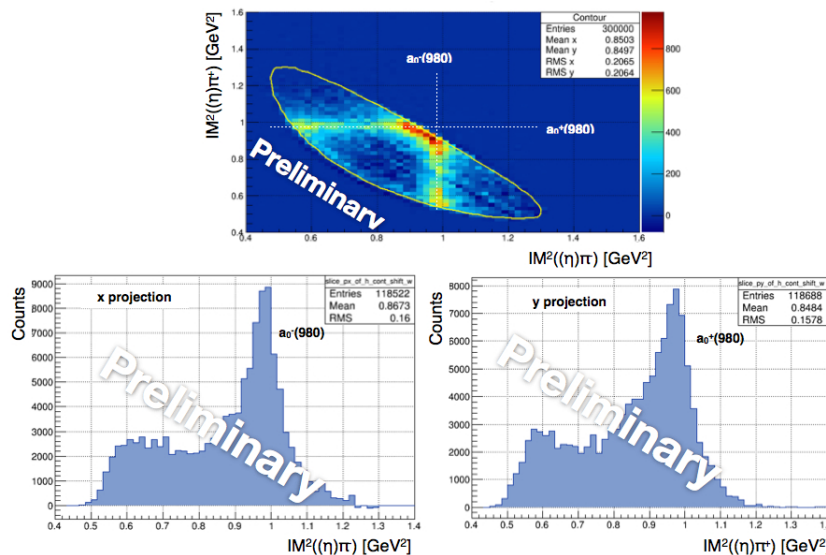
Figure 2: The sWeighted Dalitz plot of the $f_1(1285)$ meson decay in the $(\eta)\pi^+\pi^-$ channel. Even if the data are not yet acceptance corrected, it should be noted the presence of the "stripes" related to the $a^{\pm}(980)$ mesons, bound states of the $\eta\pi^+$ and $\eta\pi^-$ couple respectively

Each calculated sWeight is then associated to the corresponding event in the Dalitz, obtaining a Dalitz Plot with an enhanced signal over background ratio (see fig. 2). Without going too

deep into technicalities of the method (see ref. [19]) we can review some basics of sPlot and its application to the $f_1(1285)$ decay Dalitz. The starting point is the spectrum of the invariant mass of $(\eta)\pi^+\pi^-$, (left panel), where both the non-resonant background contribution and the signal ($f_1(1285)$ mass) contribution are present. A Probability Density Function (PDF) is defined for the background shape F_b (*i.e.* a 4th Chebychev Polynomial) and for the signal F_s (*i.e.* a Breit-Wigner function) (see fig.1). A maximum likelihood fit is then performed on the $(\eta)\pi^+\pi^-$ invariant mass and the fitted functions F_s and F_b are used to evaluate the sWeight (W_s) according to the formula:

$$W_s = \frac{V_{ss}F_s + V_{sb}F_b}{N_sF_s + N_bF_b} \qquad (1)$$

where the V_{ss} and V_{sb} are the covariance matrixes (defined in [20]), which are evaluated event by event, and N_s and N_b are the number of signal and background events respectively. By simply weighting by sWeight value each event in the Dalitz plot, univocally determined by the couple of values $(IM^2((\eta)\pi^+), IM^2((\eta)\pi^-))$, it is possible to obtain the background subtracted Dalitz plot as shown in fig. 2.

6. Conclusions

Considering the results reported in the previous section, it should be noted that even if the data are not yet acceptance-corrected, there is a sizable contribution of the two mesons $a_0^{\pm}(980)$ in the $f_1(1285)$ decay, whose contribution is generally quite elusive because of the quite huge background. In particular the projections of the sWeighted Dalitz shows a signal over background ratio which is of the order a factor five better and a statistics that is at least 70 times larger than the one available in literature [21–23]. The application of the sPlot method seems to be very effective and may be applied to data that will collected in the next years by the MesonEx experiment, allowing a PWA investigation to search for new physics. In particular the good performances in terms of rate capability, resolution and an almost full acceptance, makes MesonEx a privileged observation point to study the exotic hybrid mesons.

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