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Gluonic Excitations and the GlueX experiment

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Abstract. The physics goals of the GlueX experiment and theoretical expectations for exotic mesons are presented.

1. Introduction

The main physics goal of the GlueX experiment proposed for the 12 GeV upgraded Jefferson Lab is to map out the light quark meson spectrum up to $2.5 - 3$ GeV with the emphasis on gluonic excitations. The light mesons follow the pattern of $SU(3)$ flavor multiplets supporting the simple picture of the quark-antiquark ($Q\bar{Q}$) pairs bound by a gluonic flux tube. The flux tube is responsible for the linear Regge trajectories. Fur such systems the spin, J, parity, P and charge conjugation, C quantum numbers can be related to the symmetry properties of the quark-antiquark wave function and expressed in terms of the $Q\bar{Q}$ quantum numbers, $P = (-1)^{L+1}$, $C = (-1)^{L+S}$. The spin J is a vector sum of the total spin of quarks, S and the orbital angular momentum, L. It follows that certain J^{PC} quantum numbers, *e.g.* $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \cdots$ cannot be attributed to a valence $Q\bar{Q}$ pair. If particles with such quantum numbers, referred to as exotic mesons, exist in addition to the quark-antiquark component their valence structure must contain other degrees of freedom. It is expected that production of more quark-antiquark pairs is associated with braking of the chromo-electric flux and hadron decay. Thus a natural candidate for the additional degree of freedom is a low-energy excitation of the flux tube itself. As we will discuss below, there is evidence from lattice simulations that such excitations might exist and lead to a $J^{PC} = 1^{-+}$ exotic multiplet with mass below 2.5 GeV. Since in this picture exotic mesons originate from a mix of quark-antiquark and gluonic excitations they are also refereed to as exotic hybrids. However, it should be noticed that while existence of spin-exotic mesons is an experimental issue their hybrid interpretation is theory/model dependent.

2. Ordinary Mesons vs Gluonic Excitations

Since the light pseudoscalar mesons with $J = 0$ are protected with respect to strong decays their properties, including including partial information about their quark structure (through measurements of form factors and structure functions) are well determined [1]. The first multiplet of $Q\bar{Q}$ excited states has spin, $J = 1$, and also contains well established resonances, the ρ, K^*, ϕ and ω mesons. These have typical widths of the order of 100 MeV due to allowed hadronic decays to pairs of $J = 0$ pseudoscalar mesons. There is of the order of a dozen well established higher mass states with spin up to $J = 4$ with well established location on Regge trajectories. Even though QCD should in principle predict the location of resonances, in the absence of a first principle approach (lattice techniques have so far not been used to compute strong decay characteristics) the least model dependent method for identifying resonances comes from analysis of Regge trajectories [2]. Other methods, based for example on studies of energy dependence of individual partial waves may suffer from ambiguities associated with ad hock parametrizations of the amplitudes [3]. With recent developments in the description of low energy paramtrizations based on chiral properties of meson-meson interactions, progress has been mad in establishing properties of less known states like the σ meson [4, 5, 6]. There is, however, still a large number of states that have not been well established. The GlueX experiment will map out the meson spectrum with unprecedented statistics using photo-production which is a complementary reaction mechanism to other studied so far (which include hadro-production with pion, kaon, or proton beams, or heavy meson decays). With 9 GeV photons the mass range extends up to $2.5 - 3$ GeV and will cover the region where the light exotic multiplet is expected. At these energies the reaction mechanism is expected to be dominated by peripheral production, in naive terms corresponding to scattering of the meson cloud around the proton target. Peripheral production has been used for producing meson resonances in he past. Most recently high statistics data from E852 experiment at BNL using 18 GeV pi^- beam on hydrogen target has been analyzed and $J^{PC} = 1^{-+}$ exotic meson candidates have been reported. In the $\eta\pi^-$ and $\eta\pi^0$ decay channels a weakly mass dependent exotic P-wave has been found and originally parametrized as a resonance with mass $M = 1400$ MeV and width of the order of $300 - 400$ MeV [7]. A subsequent analysis has, however put the single resonance interpretation in question by showing that such parametrization does not reproduce all $M = \pm 1, 0$ helicity amplitudes [8]. Another exotic wave was reported in the $\eta'\pi^-$ channel. In magnitude, this amplitude turned out to be one of the dominant waves in the mass range covered, from threshold up to 2 GeV, and comparable to only one other big wave with $J^{PC} = 2^{++}$ dominated by the a_2 resonance [9]. Resonance parametrization of the P-wave in the $\eta'\pi^-$ system gives mass close to $M = 1600$ MeV and large width $\gamma = 340$ MeV. An alternative parametrization of this wave has been presented in a couple channel analysis which included the $\eta\pi^-$ and was also used to describe all other significant partial waves 0^{++}, 2^{++} [10]. As a result it was found that the exotic enhancement in the $\eta'\pi^-$ system may have origin in the residual $\eta'\pi^-$ attraction. A similar but much weaker attraction exists also in the $\eta\pi^-$ channel and is consistent with the $\eta\pi$ P-wave spectrum. To settle this issue a more comprehensive analysis which further constraints the underlying interactions to comply with crossing relations and Regge behavior should be performed.

Exotic signals were also reported in more complicated final states; in $\pi^+\pi^-\pi^-$ at 1600 MeV [11] in $\eta\pi^+\pi^-\pi^-$ [12] and in $\pi^+\pi^-\pi^-\pi^0\pi^0$ [13] at 1700 MeV and 2000 MeV. It should be noticed that these states have all being determined by fitting partial waves to a combination of Briet-Wigner resonances which for broad resonances (all of these, possibly with the exception of the 3π channel have widths of the $300 - 400$ MeV) may not be the best parametrization of the amplitudes. In summary, the 1600 GeV region does seem to indicate presence of an exotic, 1^{-+} wave in various channels.

In Fig. 1 we show the $\eta'\pi^-$ and $\eta\pi^-$ spectra and their partial wave decomposition. The lines represent a result of theoretical fits to the angular distribution whose mass dependence arises through a residual meson-meson interaction, as discussed above. The range of the interaction and the overall production strengths were fit to the data, while the strength of the underlying meson-meson interaction was constrained from an effective lagrangian [14].

3. Theoretical Expectations

Much of our the data on light quark spectroscopy can be well reproduced by non-relativistic or semi-relativistic models based on the valence constituent quark model. The constituent quarks

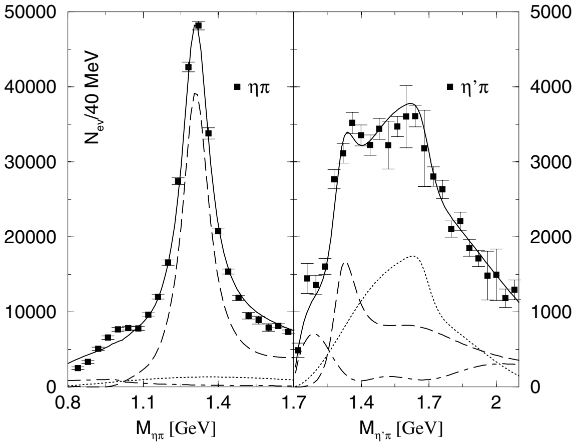

Figure 1. The $\eta\pi^-$ (left) and $\eta'\pi^-$ (right) spectra from a coupled channel analysis of the E852 data [9, 10]. The data points represent acceptance corrected number of events and the lines are the results of the partial wave analysis as described in the text (S-wave: dashed-dotted line, P-wave: dotted line, D-wave: dashed line, and total: solid line)

represent effective, massive, quasi-particles which cary flavor and spin quantum numbers. In this non-relativistic picture gluons lead to effective interactions which confine the quarks and at short distances are matched with perturbative QCD. An effective potential for non-relativistic quarks, has been computed on the lattice and is well reproduced by the standard "Coulomb+linear", Cornell-type potential. More recently a different family of potentials has been computed [15]. These arise from integrating out the gluon degrees of freedom projected onto configurations which have quantum numbers different from those of the gluonic vacuum in the presence of non-relativistic quarks. These are shown in Fig. 2. In the Born-Oppenheimer approximation, with fast gluons integrated before the slow, non-relativistic quarks, these new potentials bind the quarks and produce hybrid meson spectrum. For heavy quarks it can be compared with direct lattice calculations of the hybrid meson spectrum, while for light quarks it can by used for development of models of hybrid mesons and their decays in the spirit of the constituent quark model. From direct lattice computations of hybrid masses it is found that the exotic mesons with the J^{-+} quantum numbers are the lightest and for $u\bar{u}/d\bar{d}$ exotics the 1^{-+} state is expected around 1.8 and 2 GeV [16, 17, 18] with a systematical uncertainty of about 200 MeV estimated on the basis of chiral extrapolations [19]. Similarly, in the heavy quark sector lattice results indicate that it takes approximately 1 GeV to excite the gluonic filed (which is of the same order as the spacing between the ground state $Q\bar{Q}$ potential and the lowest one from the family of the excited gluon configurations at a distance of 1 fm) . Thus the enhancement in several channels in the 1^{-+} wave at 1600 GeV region singled out by the data on meson production could indeed have some overlap with gluonic excitaionts.

The theoretical expectations for widths of exotic mesons are less robust, however arguments based on the $1/N_c$ expansion lead to expectations that exotic mesons should have widths comparable to those of normal $Q\bar{Q}$ mesons [20]. Within the Born-Oppenheimer approach discussed above it was also shown, (see Fig. 2) that the $Q\bar{Q}$ wave function of an exotic meson is compact *i.e.* does not extend beyond 1.2 fm in the relative coordinate where quark pair creation is expected to take over [15]. Finally various model calculations tend to find similar results for exotic meson decay modes [21, 22]. For example it is expected that the dominant decays of the 1^{-+} state will be to the so called $P+S$ two meson final states, with one meson with the $Q\bar{Q}$ pair in the relative P-wave and the other with the $Q\bar{Q}$ in the relative S-wave *e.g.* $b_1\pi$, f_1,π. The largest $S+S$ mode is predicted to be the $\rho\pi$ and the expected widths are given in Table 1. The $\eta\pi$ mode is predicted to be very small, however η and η' may not have a simple constituent quark representation due to the axial anomaly and thus these later predictions might be less reliable.

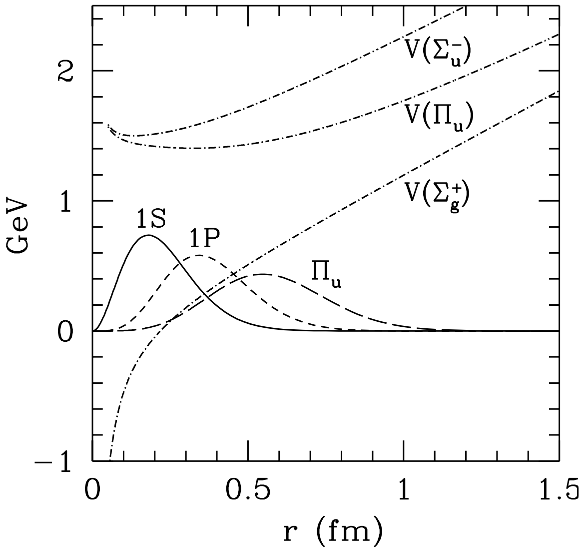

Figure 2. The $Q\bar{Q}$ potentials and corresponding $Q\bar{Q}$ wave functions. The $\Sigma^+ g$ is the potential corresponding to the gluonic ground state and is well approximated by a Coulomb potential at short distances and a linearly rising potential at large distances. The Π_u and Σ_u^- are the $Q\bar{Q}$ potentials for low lying gluonic excitations. The labeling of the potentials follows the notation used for analogues potentials of diatomic molecules. The $1S$ and $1P$ are the S and P wave functions obtained from solving the Schrödinger equation with the Σ_g^+ potential, and the $1P_{\Pi_u}$ is the exotic meson wave function obtained for the Π_u potential [15].

Table 1. Expected widths for the dominant decays of a $M = 1.8$ GeV $J^{PC} = 1^{-+}$ exotic mesons from two different models

Decay Mode	Width [MeV] Ref. [22]	Width [MeV] Ref. [21]
$b_1\pi$	51 (S-wave) 11 (D-wave)	71 (S-wave) 1 (D-wave)
$f_1\pi$	14 (S-wave) 7 (D-wave)	9 (S-wave) <1 (D-wave)
$\rho\pi$	12	13

4. Role of Photo-production

High energy, peripheral production is dominated by t-channel processes and respect a characteristic hierarchy of exchanges. Processes which do not require quantum numbers to be exchanged (charge, flavor, baryon number) are dominant and the more quantum numbers have to be exchanged to satisfy conservations laws the smaller the amplitude. It is also observed that peripheral processes are dominated by s-channel helicity conservation. Form lattice calculations discussed above and various models it also follows that the dominant $Q\bar{Q}$ component of the $J^{PC} - 1^{-+}$ exotic hybrid wave function has the quark pair in spin-1. This state is coupled to the excited gluon mode which is in a relative P-wave with respect to the $Q\bar{Q}$. It is thus expected that peripheral production of exotic hybrids will be enhanced for photons which are a virtual $Q\bar{Q}$ state with spin-1 with respect to pseudoscalar beams (*e.g.* pions), which correspond to a spin-0 $Q\bar{Q}$ system. This simple expectations have been verified in [23] where a specific, t-channel exchange model has been studied. Assuming that the ratio of the 1^{-+} (exotic) to the 2^{++}, a_2 production is of the order of 10% when produced with pion beams one finds that the exotic wave becomes enhanced in the forward direction in photo-production as a consequence of helicity conservation and that the ratio of the exotic to the a_2 production could increase by as much as a factor of $5 - 10$.

There exists data from SLAC on meson photo-production in the energy range relevant for the GlueX experiment, albeit of rather low statistics [24]. The 3π mass spectrum observed in photo-production has indeed a different structure then the 3π spectrum produced with pion

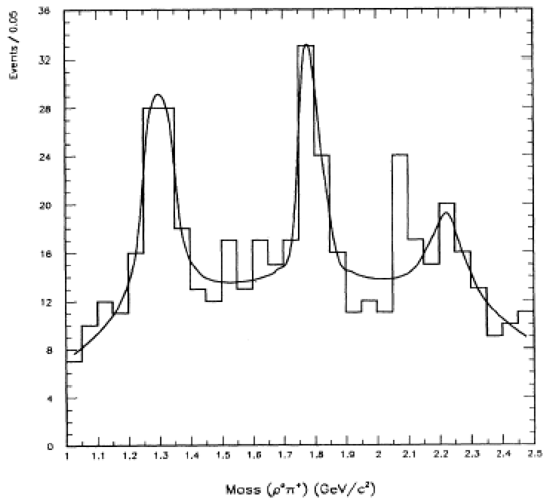

Figure 3. The 3π mass spectrum in 19 GeV photo-production from Ref. [24]. The left peak corresponds to the a_2 and the right one is consistent with the yield expected for exotic 1^{-+} production.

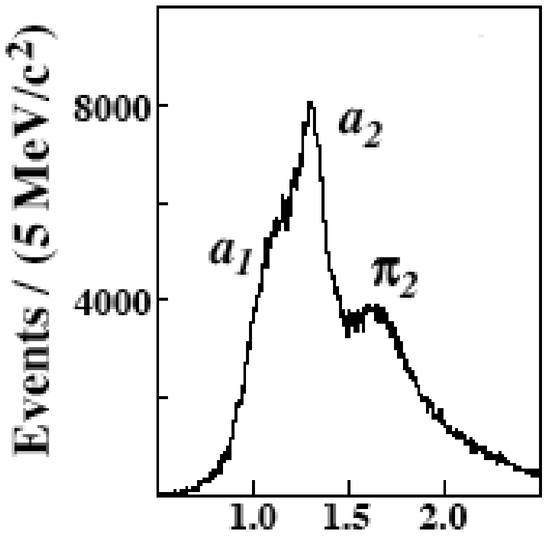

Figure 4. The 3π mass spectrum produced with 18 GeV pions from [11]

beams. In both cases a peak at $M_{3\pi} = 1.3$ GeV is seen corresponding to the a_2 production, while the a_1 (1^{++}) and the π_2 ((2^{-+})) seem to be suppressed in photo-production. Instead the enchantment in the 3π photo-production spectrum seen at around 1700 GeV is consistent with expectations for 1^{-+} production [25].

5. The GlueX Experiment

The optimal photon energy for the GleX energy is 9 GeV. This comes from considering the meson mass range to be covered, the requirements for linear polarization and for minimizing the overlap with baryon resonance region and minimizing the electromagnetic backgrounds. Partial wave analysis requires that the entire event be kinematically identified , all particles detected, measured and identified. It is also important that there be sensitivity to a wide variety of decay channels to test theoretical predictions for decay modes. The detector should be hermetic for neutral and charged particles, with excellent resolution and particle identification capability. The description of the detector, photon beam-line and the experimental hall design can be found in [26].

5.1. Acknowledgments

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6. References

[1] Eidelman S et al. 2004 *Phys. Lett.* B **592** 1
[2] Collins P D B and Squires E J *Regge Poles in Particle Physics* (Springer-Verlag, Berlin)
[3] Castillejo L, Dalitz R H, and Dyson F J (1956) *Phys.Rev.* **101** 453
[4] Oller J A and Oset E (1999) *Phys.Rev.* D **60**
[5] Pelaez J R and Yndurain F J (2004) *Phys.Rev.* D **69**
[6] Ananthanarayan B, et al. (2001) *Phys.Rept.* **353** 207
[7] Thompson D R, et al. (1997) *Phys.Rev.Lett.* **79** 1630

[8] Dzierba A R, et al. (2003) *Phys.Rev.* D **67** 094015
[9] Ivanov E I, et al. (2001) *Phys.Rev.Lett.* **86** 3977
[10] Szczepaniak A P, et al. (2003) *Phys.Rev.Lett.* **91** 092002
[11] Adams G S, et al. (1998) *Phys.Rev.Lett.* **81** 5760
[12] Kuhn J , et al. (2004) *Phys.Lett.* B **595** 109
[13] Lu M, et al. (2004) *e-Print Archive: hep-ex/0405044*
[14] Bass S D and Marco E (2002) *Phys.Rev.* D 65 057503
[15] Juge K J, Kuti J, and Morningstar C J (1998) *Nucl.Phys.Proc.Suppl.* **63** 326
[16] Lacock P, et al. (1997) *Phys. Lett.* B **401** 309
[17] Bernard C, et al. (1997) *Phys. Rev.* D**56** 7039
[18] Bernard C, et al. (2003) *Phys. Rev.* D**68** 074505
[19] Thomas A W and Szczepaniak A P (2002) *Phys.Lett.* B**526** 72
[20] Cohen T D (1998) *Phys.Lett.* B **427** 348
[21] Page P R , Swanson E S, and Szczepaniak A P (1999) *Phys.Rev.* D**59** 034016
[22] Isgur N, Kokoski R, and Paton J (1985) *Phys.Rev.Lett.* **54** 869
[23] Szczepaniak A P and Swat M (2001) *Phys.Lett.* B**516** 72
[24] Condo G T, et al. (1993) *Phys.Rev.* D**48** 3045
[25] Afanasev A V and Szczepaniak A P (200) *Phys.Rev.* D**61** 114008
[26] A.R. Dzierba, hep-ex/0106010.