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MESON SPECTROSCOPY WITH HIGH ENERGY PHOTON BEAMS AT JLAB*

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The physics motivation and current status of the Hall D project at JLab is reviewed.

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1. Introduction: historical background

The goal of the Hall D project is to carry out experimental studies of meson spectrum in the 1.5–2.5 GeV mass range, using real, linearly polarized photons. The primary goal is to identify exotic mesons and map out their production and decay characteristics.

The effort was initiated at a workshop at Indiana University in 1997. Since then, 10 workshops were organized by a collaboration which currently includes over 80 physicists from 20 institutions. In January 1999 the Hall D proposal was presented to the JLab Program Advisory Committee. Following PAC recommendation an external review of the project was conducted in December of 1999. The review committee, recognizing the fundamental role of exotic meson spectroscopy in understanding QCD and the potential of this experiment, recommended that a full conceptual design report be prepared. More information on the current status of the project can be found in [1].

2. Exotic mesons

Exotic mesons play a special role in meson spectroscopy. Exotic mesons are defined as states whose spin, parity and charge conjugation quantum numbers, J^{PC} do not belong to a sequence that could be associated with a quark–antiquark system, for which one has

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$$P_{Q\bar{Q}} = (-1)^{L_{Q\bar{Q}}+1} ,$$
$$C_{Q\bar{Q}} = (-1)^{L_{Q\bar{Q}}+S_{Q\bar{Q}}} . \quad (1)$$

Here $\vec{S}_{Q\bar{Q}}$, $\vec{L}_{Q\bar{Q}}$ and $\vec{J}_{Q\bar{Q}} = \vec{S}_{Q\bar{Q}}+\vec{L}_{Q\bar{Q}}$ are the spin, orbital and total angular momentum of the quark–antiquark pair. Thus, in particular, states with

$$J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \ldots \quad (2)$$

are exotic. As a consequence, exotic mesons cannot be described in terms of the valence quarks alone.

2.1. Theoretical considerations

Even though, dominance of valence quarks hadron structure and interactions is not a rigorous prediction of QCD, phenomenologically, valence approximation has been quite successful. In fact, essentially all constituent models of hadrons are limited to the valence region. As such, however, valence models do not give much insight into the dynamical origins of the effective interaction between quarks. Thus, in current phenomenology confinement and dynamics of low energy gluons enter indirectly *e.g.* may be constrained by hyperfine or spin–orbit interactions [2]. Exotic mesons, which by definition go beyond the valence quark dominance directly probe gluon dynamics and in principle would allow study of the gluon propagator, quark pair production mechanisms in presence of gluonic excitations and the nature of residual hadron–hadron interactions.

Current lattice simulation predict the ground state exotic meson to have $J^{PC} = 1^{-+}$ and mass around 1.9–2 GeV [3]. Analysis based on $1/N_c$ expansion suggests that decay widths of exotic mesons should scale like $1/N_c$ *i.e.* be comparable to the widths of ordinary meson resonances [4]. It is quite possible, however, that the current lattice estimates do not yet represent the physical masses since corrections from quark loops (unquenching) and corrections due to finite, and large quark masses used (chiral extrapolation) may be important. These are difficult to implement in numerical simulations and get further insight into the underlying dynamics, theoretical models of exotic mesons have been studied. These can be divided into three classes according to the way they describe gluonic degrees of freedom: constituent models [5], bag models [6] and flux tube [7] models. In the constituent model gluons are treated in a similar way to the constituent quarks. The exotic meson wave function can be constructed by coupling radial, spin and orbital motion of a $Q\bar{Q}$ pair to that of a $J^P = 1^-$, transverse magnetic, constituent gluon. Unfortunately no detailed prediction for exotic meson spectrum exists and there are still uncertainties in the underlying effective interaction. The problems with the model have been pointed out in [8] where the constituent gluons spectrum was studied in presence of a static $Q\bar{Q}$ pair. When quarks are infinitely heavy, gluon wave function can be defined in terms of the projection of the total (gluon) angular momentum along the $Q\bar{Q}$ axis, $\Lambda = 0, 1, 2 \cdots = \Sigma, \Pi, \Delta, \cdots$, combined parity and charge conjugation, $PC = g(+1), u(-1)$ and the $Y = \pm 1$ parity corresponding to reflection in a plain containing the $Q\bar{Q}$ axis. For a purely central potential between constituent gluons and the quarks one expects S-wave gluon orbital to be the lowest energy state, which translates into the $\Lambda^Y_{PC} = \Pi^{\pm}_g$ configuration for static quarks to be of the lowest energy.

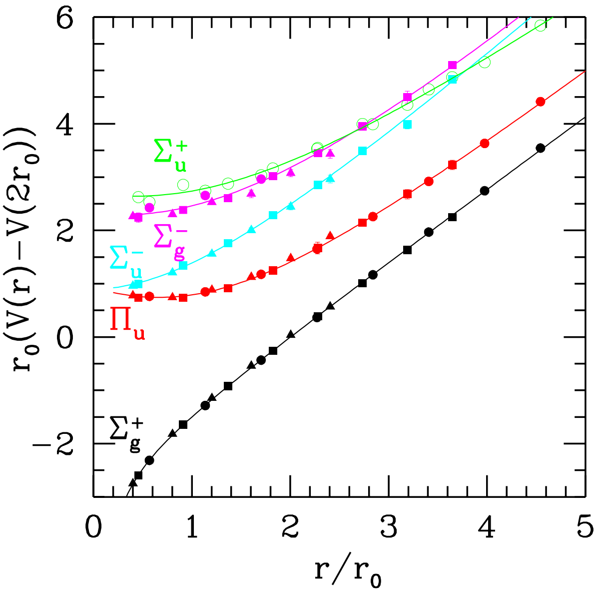

Fig. 1. Lattice predictions for the energy of a $Q\bar{Q}$ system as a function of the $Q\bar{Q}$ separation (in units of $r_0 = (430\ \text{MeV})^{-1}$) for various configurations of the gluonic field. From Morningstar *et al.* [9].

Lattice simulations [9], however, (Fig. 1) predict the $\Pi\pm_u$ configuration for the ground state. This implies that, if the constituent gluon model is to be taken seriously, the effective potential should have a significant non-central component.

In the bag model, discrete modes of the gluon field are obtained by imposing boundary conditions on the chromomagnetic field at the surface of the bag. It turns out that this leads to the $J^P = 1^+$, transverse electric being of lower energy then the $J^P = 1^-$ configuration [6]. This is consistent with lattice results. Similar results are obtained in the flux tube picture, where gluons correspond to collective, phonon excitations of a nonrelativistic string representing the chromoelectric flux between the quarks.

In summary, lattice data and models consistently predict that lowest gluonic orbitals have $J^P = 1^+$ and thus (in the constituent language) come from coupling a spin-1^- object to one unit of orbital angular momentum.

When models for exotic mesons are supplemented with a quark–antiquark production mechanism one can test the underlying structure by studying exotic meson decays. It is usually found that two-meson exotic decays are dominated by $S+P$ channels *i.e.* decays with one of the final state mesons having quarks in the S-wave orbital and the other in P-wave [10]. Individual models, however, lead to significantly different predictions for ratios of partial waves (if there is more then one) contributing to a given final state. As summarized in Table I, for the $J^{PC} = 1^{-+}$ exotic it is expected that the $b_1\pi$ and $f_1\pi$ decay channels dominate followed by the $\rho\pi$ channel. In the $b_1\pi$ decay channel the S wave is expected to be much larger then the D wave in the model of [11] which is not predicted in [10]. Both models are based on the flux tube description with different assumption on the $Q\bar{Q}$ formation process.

TABLE I

Predicted, dominant $J^{PC} = 1^{-+}$ exotic meson decay modes

$J^{PC} = 1^{-+}$(1.8 GeV)	$b_1\pi$ [MeV]	$f_1\pi$ [MeV]	$\rho\pi$ [MeV]
Model I [11]	S 73	S 9	P 13
	D 1	D 0.04	
Model II [10]	S 51	S 14	P 12
	D 11	D 7	

2.2. Role of photoproduction

The predicted, not too small coupling of the 1^{-+} exotic to the $\rho\pi$ channel is encouraging. So far the best experimental candidate for the exotic meson comes from the E852 BNL experiment [12]. In this experiment the reaction $\pi^- p \to (\rho^0\pi^-)p \to \pi^+\pi^-\pi^- p$ was studied at $E = 18$ GeV beam energy. The $\rho^0\pi^-$ system was observed to be dominated by the 2^+ partial wave with maximum at $M_{\rho\pi} \sim 1.3$ GeV due to decay of the a_2 resonance, and the 2^- wave near 1.6 GeV from the decay of the π_2 resonance. A significant 1^- resonant wave, however, was also fund at $M_{\rho\pi} \sim 1.6$ GeV. Since the $\rho^0\pi^-$ system has negative G parity and it belongs to an isovector multiplet its neutral partner will have positive charge conjugation and thus the observed resonance should be a member of an isovector exotic multiplet. Even though the $\rho\pi$ is not expected to be the dominant decay channel (the $b_1\pi$ decay channel is currently being analyzed) it is possible that theoretical predictions will have to be modified once final state interaction effects are taken into account. For example strength in the $b_1\pi$ channel can be reduced in favor of the $\rho\pi$ channel as a result of rescattering via ω exchange (this effect may be significant due to large $b_1 \to \omega\pi$ decay width and large $g_{\rho\omega\pi}$ coupling).

The majority of exotic meson searches have so far been performed in hadronic reactions. It is possible, however, that exotics may be much easier to produce with real photons instead. The argument is simple and goes as follows. In the flux tube model (and similarly in other) the intrinsic parity and charge conjugation of low lying exotic mesons are given by

$$\begin{aligned} P &= P_{Q\bar{Q}}(-1)^{L-L_{Q\bar{Q}}+1}\,, \\ C &= C_{Q\bar{Q}}(-1)^{L-L_{Q\bar{Q}}}\,, \end{aligned} \tag{3}$$

where the quark–antiquark intrinsic parity, $P_{Q\bar{Q}}$ and charge conjugation, $C_{Q\bar{Q}}$ are given in Eq. (1) and L is the total angular momentum of the $Q\bar{Q}$ gluon system. In high energy, low t peripheral production photon scatters off a meson cloud with a large probability of fluctuating first into a vector, 1^{--} meson, (Vector Meson Dominance) *i.e.* to a $Q\bar{Q}$ system with $S_{Q\bar{Q}} = 1$ and $L_{Q\bar{Q}} = 0$. Without the necessity of fliping quark helicities (S-channel helicity conservation) the meson cloud can "pluck" the flux tube, promoting it to the first excited state (as discussed above, the low lying exited glue states are expected to have one unit of orbital angular momentum) and thus changing the charge conjugation resulting in an exotic state,

$$\gamma \xrightarrow{\text{VMD}} \rho\ (J^{PC} = 1^{--}) \xrightarrow{\text{OPE}} \pi_1\ (J^{PC} = 1^{-+})\,. \tag{4}$$

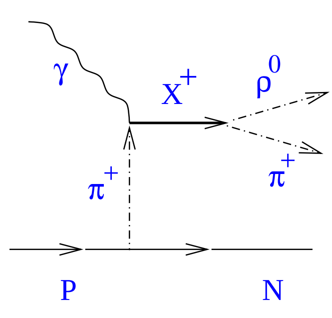

Fig. 2. Expected, dominant photoproduction mechanism of the exotic meson resonance.

The charge exchange, peripheral $\gamma p \to (\rho^0\pi^+)n \to \pi^+\pi^-\pi^+n$ reaction, which is expected to be dominated by one pion exchange (OPE), may thus be a preferred reaction for exotic production (Fig. 2).

The existing photoproduction data is very limited, however, interesting signatures are found in the old SLAC bubble chamber experiments which are in fact quite different from what was observed with *e.g.* pion beams.

Condo *at al.* [13] studied the reaction $\gamma p \to X^+ n \to (\rho^0\pi^+)n \to \pi^+\pi^-\pi^+n$ at two average photon energies $E_\gamma \sim 19.4$ GeV and $E_\gamma \sim 4.8$ GeV. The observed 3π mass spectrum is dominated by the a_2 resonance, similar to the E852 case, but no visible a_1 signal nor π_2 is seen. Instead, a sharp peak at $M_{3\pi} \sim 1.77$ GeV appears. Limited statistics does not allow for an identification of the underlying J^{PC}, however, the analysis is consistent with it being $J^{PC} = 1^{-+}$, 2^{-+} or 3^{++}. The benchmark, a_2 production was found to be consistent with OPE with absorption. In Ref. [14] charge exchange photoproduction of the 3π system was studies using relativistic Lippmann–Schwinger formalism in the isobar model coupled with the OPE production mechanism. The calculated 3π mass spectrum agrees with the measured one, and in particular, the enhancement at $M_{\rho\pi} \sim 1.7$ GeV can easily be accounted for if an exotic 1^{-+} sate is included with mass consistent with the E852 measurement and $\gamma\pi$ and $\rho\pi$ couplings consistent with theoretical expectations. The model also explains the relative weakness of the a_1 and the π_2 contributions. The predicted mass spectrum is shown in Fig. 3. The four lines are obtained using electromagnetic widths of the exotic meson of, $\Gamma_{\pi_1 \to \pi\gamma} = 400$ keV (higher) and 200 keV (lower) and strong coupling to the $\rho\pi$ channel, $\Gamma_{\pi_1 \to \rho\pi} = 100$ MeV for the solid lines and $\Gamma_{\pi_1 \to \rho\pi} = 200$ MeV for the dashed lines.

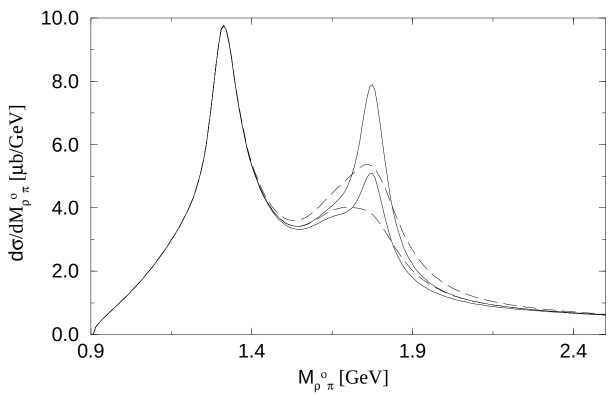

Fig. 3. Theoretical prediction for the 3π mass spectrum in the reaction $\gamma p \to \pi^+\pi^-\pi^+n$ at $E_\gamma = 8$ GeV. The peak at $M_{3\pi} \sim 1.7$ GeV is due to an exotic resonance.

Another important feature of photoproduction is polarization. In peripheral production understanding of the production mechanisms plays and important role in theoretical analysis and together with the partial wave analysis provides information on parameters of produced resonances. It turns out that linear polarization is necessary to isolate natural from unnatural parity exchanges and it is very helpful in the partial wave analysis. The connection between liner polarization and naturality of particles participating in the reaction follows from considering transformation properties under parity. At the production vertex parity conservation implies

$$A_{\gamma \to eX}(\lambda_\gamma, \lambda_X) = \tau_e \tau_X (-1)^{\lambda_X - \lambda_\gamma} A_{\gamma \to eX}(-\lambda_\gamma, -\lambda_X)\,, \tag{5}$$

where $\tau(= P(-1)^J)$ is the naturality of either the exchanged particle, (e) or the produced resonance (photons whose linear polarization, in the rest frame of the resonance is either in direction perpendicular to the production plane, $|y\rangle = i/\sqrt{2}\,(|\lambda_\gamma = +1\rangle + |\lambda_\gamma = -1\rangle)$ or parallel to it, $|x\rangle = 1/\sqrt{2}\,(|\lambda_\gamma = -1\rangle - |\lambda_\gamma = +1\rangle)$, Eq. (5) implies

$$\begin{aligned} A(x,x),\ A(y,y) \ &\propto\ (1 + \tau_e \tau_X)\,, \\ A(x,y),\ A(y,x) \ &\propto\ (1 - \tau_e \tau_X)\,. \end{aligned} \tag{6}$$

Here $A(i,j)$ represents production amplitude of a resonance linearly polarized along the $j(= x, y)$ direction due to a photon linearly polarized along the i direction. It thus follows that, if OPE dominates, then direction of linear polarization of unnatural parity resonances, *e.g.* a_1 or π_2 is parallel to the direction of photon polarization and if a natural parity resonance is produced (*e.g.* a_2 or the exotic, π_1) its direction of polarization should be perpendicular to photon polarization. It is possible to trace orientation of polarization of the produced resonance to the angular distribution of produced pions and find asymmetries which will discriminate between the two types of resonances effective providing a filter of the exotic [14].

3. Experimental considerations

Identification of exotic mesons and determination of their decay characteristics will require detailed partial wave analysis. This can be achieved provided high statistics is available and the detector is hermetic minimizing acceptance correction. The schematic layout of the Hall D detector is shown in Fig. 4. The two major elements, the superconducting solenoid and the lead glass calorimeter already exist. The magnet was used originally in the LASS experiment at SLAC, and the LGD was used in the E852 experiment. After CEBAF energy upgrade electron beam will reach 12 GeV and

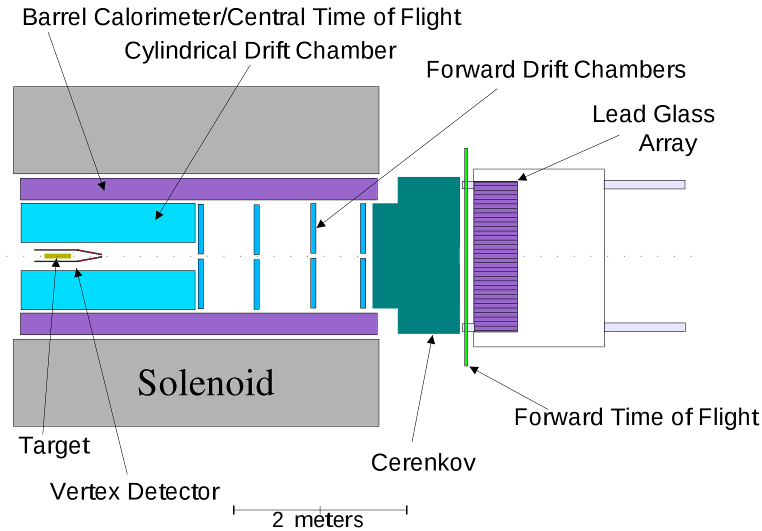

Fig. 4. Schematic layout of the Hall D detector

for Hall D purposes, via coherent bremsstrahlung it will be used to produce high flux, $10^7\gamma$/s of linearly polarized photons. With such rates the data sample produced in one year will already exceed the existing world data on photoproduction by several orders of magnitude.

The is a number of factors which determine the optimal energy range. These include the requirement of high linear polarization, high meson yields and the dominance of peripheral production. Coherent bremsstrahlung allows for high degree of linear polarization while maintaining high fluxes. The degree of polarization, however, decreases with photon energy. On the other hand, higher energies are desirable in order to decrease the effects of the overlap with baryon resonances and to minimize the effects from a finite, minimum momentum transfer. Combination of such effects leads to the optimal energy being between 8 and 9 GeV which makes the JLab to be a unique facility for exotic meson studies.

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