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# Lessons from Hadron Phenomenology

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## Abstract

Meson spectra can be well approximated by a specific form of a nonlinear Regge trajectory which is consistent with a finite number of bound states. This may have important consequences for experiment, and may be a hint for the theory.

## 1 Introduction

The main effort of our light-front community has been in the past ten years to develop new techniques for solving QCD, be it DLCQ- or renormalisation-group-based methods (for review see [1]). In practice the usefulness of any procedure (which includes the question of convergence) is often determined by how well its first approximation captures the essential features of the system under consideration. This is why phenomenology can be helpful in tailoring the approximation schemes by giving us some hints of what is important for the spectra.

## 2 Regge Trajectories and Spectroscopy

One phenomenological way of describing the spectra is via Regge trajectories  $\alpha(s)$ , which can be, for the purpose of my presentation, thought of as "lines" connecting the bound states plotted in the angular momentum  $J$  vs. mass squared  $M^2$  plane,  $\alpha(s) \equiv J(M^2)$ . Table I illustrates the grouping into trajectories of the light  $I = 1$

mesons. The trajectories differing by parity (such as the vector and tensor, the first line of the Table I) would be degenerate in a non-relativistic theory; in the full theory, they are near-degenerate in the bound-state region.

$q\bar{q}$ spin		S	P	D	F	wave
S=1	vector	$\rho (1^{--})$		$\rho_3 (3^{--})$		
	tensor		$a_2 (2^{++})$		$a_4 (4^{++})$	
	axial vector		$a_1 (1^{++})$		$a_3 (3^{++})$	
	axial tensor			$\rho_2 (2^{--})$		
S=0	scalar		$a_0 (0^{++})$		$a_2 (2^{++})$	
	vector			$\rho (1^{--})$		
	pseudoscalar	$\pi (0^{-+})$		$\pi_2 (2^{-+})$		
	pseudovector		$b_1 (1^{+-})$		$b_3 (3^{+-})$	

Table I. Regge trajectories for the light  $I = 1$  mesons.  $J^{PC}$  of the given meson is shown in parentheses.

In the Veneziano model for scattering amplitudes [2] there are infinitely many excitations populating linear Regge trajectories. The Veneziano amplitude ( $s, t$  are the usual Mandelstam variables),

$$V(s, t) = \frac{\Gamma(1 - \alpha(s))\Gamma(1 - \alpha(t))}{\Gamma(2 - \alpha(s) - \alpha(t))} = \int_0^1 dx x^{-\alpha(s)}(1 - x)^{-\alpha(t)}, \quad (1)$$

only allows for a linear (or at most a polynomial [3]) trajectory,  $\alpha(s) = \alpha(0) + \alpha's$ , if the spins are finite [2]. The same picture of linear trajectories arises from a linear confining potential and the string model of hadrons (see [4] for references).

However, the realistic Regge trajectories extracted from data are *nonlinear*. For example, the straight line which crosses the  $K_2^*$  and  $K_4^*$  squared masses corresponds to an intercept  $\alpha_{K_2^*}(0) \approx 0.1$ , whereas the physical intercept is located at  $\approx 0.4$ . In addition to being disfavored by this and other experiments, linear trajectories also lead to problems in theory. (For details on both experimental and theoretical aspects, and references, see [4].)

We have argued that the nonlinearity of hadronic Regge trajectories is due to pair production which screens the confining QCD potential at large distances [5]. Because of pair production, there cannot be infinitely many bound states, and the real part of Regge trajectories will terminate in angular momentum. Once the nonlinearity of Regge trajectories is an accepted fact, the question of what specific form should be used for phenomenology arises.

We have considered a whole class of nonlinear trajectories allowed by dual amplitudes with Mandelstam analyticity (DAMA) ([6] and references therein). DAMA are the generalization of Veneziano amplitudes (1),

$$D(s, t) = \int_0^1 dx \left( \frac{x}{g} \right)^{-\alpha(s')} \left( \frac{1-x}{g} \right)^{-\alpha(t')} \quad (2)$$

where  $g > 1$  is a constant, and  $s' = s(1-x)$ ,  $t' = tx$ , and they allow for Regge trajectories of a form

$$\alpha_{j\bar{i}}(t) = \alpha_{j\bar{i}}(0) + \gamma [T_{j\bar{i}}^\nu - (T_{j\bar{i}} - t)^\nu] \quad (3)$$

where  $\nu$  is a constant restricted to  $0 \leq \nu \leq \frac{1}{2}$ ;  $\gamma$  is a universal constant;  $T_{j\bar{i}}$  is a trajectory threshold,  $\alpha_{j\bar{i}}(0)$  is its intercept, and  $i, j$  refer to flavor. We have argued that both limiting cases ( $\nu = 1/2$  and  $\nu = 0$ ) can be expected to work comparably well for lowest lying states, but the  $\nu = 1/2$ , so-called square-root, form is likely to be more realistic. Therefore, we use the square-root form for phenomenological purposes.

Assuming that Regge trajectories are of the form (3) with  $\nu = 1/2$ , we determine thresholds and intercepts of trajectories by using various experimental information. Typically, we use masses of a few known lowest lying states, and in the case of the  $\rho$  trajectory we also use the value of the intercept (which is known and well-established) found from exchange processes. The value of  $\gamma$  (the universal asymptotic slope) is fit to the  $\rho$  trajectory, and then taken as universal for all other trajectories.

The approach has more predictive power than one would naively expect. This is because the parameters for trajectories with different flavors within a multiplet are related by additivity of intercepts and additivity of inverse slopes near the origin, two requirements that are independent of which specific form is assumed for the trajectories [4]. This means in practice, that out of 20 parameters for each 5-flavor meson multiplet, only 8 are independent. We further reduce the number of parameters by requiring that the thresholds of parity-partner trajectories (such as vector and tensor in Table I) are the same. This further reduces the number of parameters for the two related multiplets from 16 to 12. We tested this assumption where there were data available, and it is well satisfied [4].

Once the parameters of the trajectories are known, masses of excited states lying on each of the trajectories under consideration can be calculated, and compared with experimental data. Where there are no data available, our results are predictions. Recall, that one of the parameters of a trajectory, in particular, its intercept, is also an observable, so the result of our fit to bound state data can be independently checked with what is known from scattering processes.

We studied vector and tensor meson trajectories, and pseudoscalar and axial-vector meson trajectories. In all of these cases, our results are in excellent agreement with both scattering and bound state data, as well as results of different methods, such as lattice QCD or sum rules.

The approach can also be applied to glueballs. We extracted parameters of the Pomeron trajectory, assuming that it, too, is of the square-root form, from the data collected by ZEUS collaboration [7]. We found a threshold of 10 GeV, much higher than that of, but consistent with what can be expected from, light mesons. The parameters yield plausible values for glueball masses [8].

Experimental consequences of the termination of Regge trajectories are intriguing. For example, we believe that  $a_6$  is likely to be the last state on the  $a_2$  trajectory. We also believe that any state above roughly 3.2 GeV that does not fit into charmonium spectra is likely to be an exotic, since according to our study light quarkonium states terminate at about 3 GeV. This leaves a large window for glueballs, since they terminate at a much higher mass. Of no less interest is the main lesson for the theory: Linear confinement is likely neither sufficient nor the most important factor determining the position of poles, not even for states as low as second or third on a trajectory. This means that if our light-cone attempts to solve QCD are to be successful beyond the ground states, they need to take into account the effect of pair production or, in other words, mixing with higher Fock states.

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