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A FRESH LOOK AT EXOTICS

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A B S T R A C T

Simple quark model considerations suggest that the least massive exotic mesons and baryons may occur close to the nucleon-antinucleon and nucleon-nucleon-antinucleon thresholds respectively. The fact that such channels are energetically open for the decay of these exotics means that both production and decay can proceed via allowed duality diagrams. We suggest three specific reactions which may permit their detection.

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Introduction

It is a common myth that the simple quark model permits no exotic mesons or baryons. A myth since we shall in fact use the model to estimate the approximate masses and quantum numbers of what might be the lowest-lying exotics. We shall then suggest three particularly clean experiments for the detection of such objects : a $K_{\frac{3}{2}}^{++}$ doubly charged, isospin $\frac{3}{2}$, strangeness +1 meson; a $\mathbf{T}_1^{++}$ doubly charged, isospin 1, strangeness +2 meson; and a Z_2^{+++} triply charged, isospin 2, strangeness +1 baryon.

Some Quark Modelling

Let us recall that the leading non-strange meson and baryon trajectories are found to have the approximate forms :

$$M_J^2 = -0.475 + 1.05 J \quad (\text{GeV})^2 \quad (1.a)$$

for the ρ - A_2 pair; and

$$M_J^2 = +0.075 + 1.05 J \quad (\text{GeV})^2 \quad (2.a)$$

for the Δ - N_ρ trajectories. These may be rewritten as :

$$M_n^2 = 2\mu^2 + (n + 3/2)\omega\sqrt{2} \quad (1.b)$$

$$M_n^2 = 3\mu^2 + (n + 6/2)\Omega\sqrt{3} \quad (2.b)$$

where $\mu^2 = -0.5 \text{ GeV}^2$, $\omega\sqrt{2} = \Omega\sqrt{3} = 1.05 \text{ GeV}^2$ and n is a principal quantum number equal to $J-1$ for the mesons and $J-\frac{3}{2}$ for the baryons. In this form Eqs. (1.b) and (2.b) resemble respectively the eigenvalue spectrum of a $q\bar{q}$ system with potential energy $\frac{1}{2}m\omega(\vec{r}_1 - \vec{r}_2)^2$ and that of a qqq system with potential energy $\frac{1}{2}m\Omega \sum_{i < j} (\vec{r}_i - \vec{r}_j)^2$. The first term of these equations is something like a rest mass contribution from each quark. We must emphasize the words "something like", for in the first place we are rather cavalierly interpreting these eigenvalues as the squares of masses : in the second place the rest mass term will contain all kinds of other effects such as those that cause the pion to be less massive than the rho; those that cause the kaon to be more massive than the pion, etc. Thus we should not be too disturbed to find that this term is negative for the trajectories in question.

Thus said, it is reasonable to suppose that $\mu^2 = -0.5 \text{ GeV}^2$ is the value to be associated with non-strange quarks in their maximum spin configuration, e.g., as in the various members of the ρ and $\Delta(1236)$ trajectories. There are, of course, two important questions that the simple quark model begs :

- i) why are there no non-zero triality bound states such as $qq, q\bar{q}\bar{q}$, etc.?
- ii) why are there no zero triality bound states of the type $q\bar{q}q\bar{q}, qq\bar{q}\bar{q}$, etc.?

These two questions are not usually separated from each other. However, if we make the separation and regard the answer to the first as being too deep for our present understanding - perhaps having to do with some superselection rule against the observability of fractionally charged particles - we may re-phrase the second question as :

at what mass might we expect to find such states as $q\bar{q}q\bar{q}, qq\bar{q}\bar{q}$, etc.?

This question can now be answered within the framework of the model discussed above.

The $q\bar{q}q\bar{q}$ Bound States

Locating the two quarks at $\vec{r}_1$ and $\vec{r}_3$, and the antiquarks at $\vec{r}_2$ and $\vec{r}_4$, the potential energy is :

$$\frac{1}{2} m \omega^2 \sum_{i-j \text{ odd}} (\vec{r}_i - \vec{r}_j)^2 + \frac{1}{2} m \Omega^2 \sum_{i-j \text{ even}} (\vec{r}_i - \vec{r}_j)^2 \quad (3)$$

Such bound states would be exotic mesons, and diagonalization of this Hamiltonian leads us to expect trajectories of the form :

$$M_n^2 = 4\mu^2 + (n_1 + 3/2)2\omega + (n_2 + 6/2)\sqrt{2(\omega^2 + \Omega^2)} \quad (4)$$

where $n_1 + n_2 = n = J - 2$ for the leading trajectory. The least massive member of this trajectory should thus have a mass squared value of

$$4\mu^2 + 3\omega + 3\sqrt{2(\omega^2 + \Omega^2)} = 4.30 \text{ GeV}^2 \quad (5)$$

In order to determine the quantum numbers of this particle, we recall that the quark wave functions must be symmetric under the interchange of any two quarks. This is the condition which enables a $\frac{3}{2}^+$ decuplet to be part of the three-quark ground state in this model. Thus we impose the symmetry condition on the two quarks and on the two antiquarks. The ground state having no orbital angular momenta among the quarks and antiquarks then contains the multiplets : $\{1\}$, $\{8\}$, $\{27\}$ with $J^P = 2^+, 1^+$ and 0^+ ; $\{1\}$, $\{8\}$ with $J^P = 0^+$; $\{10 \pm \overline{10}\}$, $\{8 \pm 8'\}$ with $J^P = 1^+$.

Here $\{ \pm \}$ indicates a pair of multiplets with opposite charge conjugation properties. Since our value for μ^2 pertains to the leading non-strange trajectories, the particle in Eq. (5) will be a member of the set $\{1\} + \{8\} + \{27\}$ with $J^{PC} = 2^{++}$. Moreover, if the empirical rule of $\sim 0.34 \text{ GeV}^2$ extra (in mass squared) for each strange quark, familiar for the best known non-exotics, continues to hold, we might expect the following masses for this $2^{++} \{27\}$ -plet *) :

$$\begin{aligned} S=0 & : M \sim 2075 \text{ MeV} \\ S=\pm 1 & : M \sim 2150 \text{ MeV} \\ S=\pm 2 & : M \sim 2230 \text{ MeV} \end{aligned}$$

The $qqqq\bar{q}$ Bound States

Placing the four quarks at positions $\vec{r}_1, \dots, \vec{r}_4$ and the antiquark at $\vec{r}_5$ gives a potential energy of

$$\frac{1}{2} m \omega^2 \sum_{i=1}^4 (\vec{r}_i - \vec{r}_5)^2 + \frac{1}{2} m \Omega^2 \sum_{i < j \neq 5} (\vec{r}_i - \vec{r}_j)^2 \quad (6)$$

The resulting spectrum then takes the form

$$M_n^2 = 5\mu^2 + (n_1 + 3/2)\omega\sqrt{5} + (n_2 + 9/2)\sqrt{\omega^2 + 4\Omega^2} \quad (7)$$

with $n = n_1 + n_2 = J - \frac{5}{2}$ for the leading trajectory. For the least massive member of this trajectory we obtain a mass squared value of

*) Since exotics contain qq and $q\bar{q}$ forces we have simply averaged the mass-squared increases per unit of strangeness observed for non-exotic mesons ($\sim 0.24 \text{ GeV}^2$) and non-exotic baryons ($\sim 0.44 \text{ GeV}^2$). Alternative prescriptions might yield different, but equally plausible, estimates.

$$5\mu^2 + \frac{3}{2}\sqrt{5}\omega + \frac{1}{2}\sqrt{\omega^2 + 4\Omega^2} = 6.36 \text{ GeV}^2 \quad (8)$$

By application of the symmetric statistics to the four quarks in the system, the particle predicted by Eq. (8) is seen to be a $J^P = \frac{5}{2}^-$ member of a $\{10\} + \{35\}$ pair of SU(3) multiplets. For these exotic baryons the leading trajectory will be accompanied by lower-lying ones whose ground state composition is :

$$\begin{aligned} \{10\}, \{35\} & \quad \text{with } J^P = \frac{3}{2}^- \\ \{8\}, \{10\}, \{27\} & \quad \text{with } J^P = \frac{3}{2}^- \text{ and } \frac{1}{2}^- \\ \{8\}, \{10\} & \quad \text{with } J^P = \frac{1}{2}^- \end{aligned}$$

Once again we apply the empirical strangeness/(mass)² relationship to estimate the masses of the various members of the $\frac{5}{2}^- \{35\}$ -plet with the result

$$\begin{aligned} S=0 & : & M & \sim 2520 & \text{MeV} \\ S=\pm 1 & : & M & \sim 2590 & \text{MeV} \\ S=-2 & : & M & \sim 2650 & \text{MeV} \\ S=-3 & : & M & \sim 2720 & \text{MeV} \\ S=-4 & : & M & \sim 2780 & \text{MeV} \end{aligned}$$

Finding Them

To detect such a dense set of "ground state" exotics would clearly be a formidable experimental task, particularly since most of these multiquark states are not obviously exotic in their charges or even in their SU(3) multiplicities. However, our task is not so much to test the quark model as to search out any exotics that may exist. We have used the model only as a guide to where it may be profitable to look, with the result that the following experimental considerations should be taken into account in the design of any future systematic searches.

First, for the purpose of ensuring that anything detected is exotic and well separated from a probably large non-exotic background one should concentrate on particles with manifestly exotic charge quantum numbers. Of

course, their isotopic partners with non-exotic charges still provide a valuable check on both the existence and the isospin of any enhancement with an unusual charge-strangeness combination. In this respect, a $\{27\}$ -plet of mesons and a $\{35\}$ -plet of baryons, were they to exist, would provide many clear signals.

Secondly, we want the production cross-sections to be as large as possible. So it is perhaps a good plan not to look for processes whose duality diagrams are of forms which are known to lead to small cross-sections for non-exotic processes, e.g., diagrams where a quark line begins and ends on the same external particle or those that can be otherwise disconnected, such as for $KN \rightarrow Z^*$ ¹⁾. To this end we can notice that the process : meson-baryon $\rightarrow$ exotic meson - (non-exotic) baryon can proceed via ordinary baryon exchange in both the s and u channels. See Fig. 1.

Consequently, if some exotic mesons have couplings of conventional strength, we might expect their production cross-sections to be of similar magnitude to that of conventional baryon exchange processes, i.e., of the order of a few microbarns ²⁾. Production of an exotic baryon can also proceed via non-exotic baryon exchange but only with the associated production of an exotic meson. See Fig. 2.

Thirdly, on account of the comparatively high masses that our exotics are predicted to have, their decay can also proceed via "allowed" diagrams : baryon-antibaryon for an exotic meson, and two baryons with an antibaryon for an exotic baryon. See Fig. 3.

Finally, three points that have a direct bearing on the detection efficiency are :

- i) one should choose processes whose final state particles are as few in number and as identifiable as possible, e.g., antineutrons are undesirable final state objects as are too many pions;
- ii) exotic particles with too many decay channels "waste" a valuable amount of detection efficiency, particularly if some of these decay channels are difficult to identify;
- iii) one should choose experiments - particularly when searching for exotic baryons - in which there is a minimum of ambiguity as to which of the detected particles result from which of the exotics produced.

The reader may amuse himself, as we did, by thinking up further possible experiments, but we would suggest the following three which fulfil all of the above criteria (the last three in particular to the maximum extent possible).

Experiment 1

The doubly charged kaon member of the $J^{PC} = 2^{++}\{27\}$ multiplet, which our quark model estimates predict at ~ 2150 MeV, should be observable in a π^+p exposure above 5.2 GeV/c, via the process :

$$\pi^+ p \rightarrow K^{++} \Lambda \quad (9)$$

$$\quad \quad \quad \searrow \quad \quad \quad p \bar{K}^+$$

This reaction was also suggested in Ref. 1).

Experiment 2

The doubly strange partner of this K^{++} , could (depending upon its precise position relative to the $p \bar{\Xi}$ threshold) present itself via its charge +2 state if the beam momentum is raised above 6.4 GeV/c :

$$\pi^+ p \rightarrow \Upsilon^{++} \Xi^0 \quad (10)$$

$$\quad \quad \quad \searrow \quad \quad \quad p \bar{\Xi}^+$$

where we have called this particle an "upsilon".

Experiment 3

Although the $\frac{5}{2}^-\{35\}$ baryon multiplet is predicted to lie somewhat below the $NN\bar{\Xi}$ threshold (if our quark model estimates are taken literally) one might observe a more massive $\{35\}$ -plet member accompanied by a singly charged, albeit exotic, antikaon in the process

$$\pi^+ p \rightarrow Z_2^{+++} \bar{K}_{\frac{1}{2}}^- \quad (11)$$

$$\quad \quad \quad \searrow \quad \quad \quad p p \bar{K}^+ \quad \quad \quad \searrow \quad \quad \quad \Lambda \bar{p}$$

Here the pion beam has a lab. momentum in excess of 14 GeV/c, and the $\{35\}$ -plet baryon in question is the triply charged, isospin 2, strangeness +1 member, denoted Z^{+++} .

A common feature of all of these reactions is a multiparticle final state containing one or two antibaryons. Since enhancements in such systems are not unknown ⁴⁾, we cannot over-emphasize the importance of following up all antibaryon hints that future production experiments might offer as to the existence of exotic mesons and baryons ^{*)}.

Concluding Remarks

One has become accustomed to seeing the quark model used for classifying and extending via predictions known phenomena. What we have attempted in the present paper is the somewhat bold step of asking the model some fairly quantitative questions about a hitherto unobserved phenomenon - one which possibly does not exist. The answer it gives us is that previous searches ³⁾ for exotic particles have been denied success on two counts : one being an energy that was usually too low; the other being a production-decay mechanism that is not favoured by the model. It suggests that future experiments concentrate on final states involving antibaryons, rather than multiply charged combinations of mesons and baryons. While it is of interest to speculate on the manner of decay of below-threshold exotics, one should make the first effort on those states that may be lurking just above these antibaryon thresholds. Not only does the quark model hint that they are there, but they may turn out - as was the case for the first non-exotic mesons and baryons discovered - to be rather cleanly separated from each other and from the background, thus enabling a spin-parity determination to be made.

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^{*)} We remind the reader that as long ago as 1968, Rosner ⁵⁾ pointed out the necessity, from the duality viewpoint, of the existence of exotic mesons with strong couplings to baryon-antibaryon channels.

R E F E R E N C E S

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FIG.1

FIG.2

FIG.3