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ELECTROMAGNETIC MIXING OF NARROW BARYONIUM STATESG.C. Rossi^{*)}

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ABSTRACT

We discuss the theoretical possibility that electromagnetic mixing in the recently discovered narrow baryon-antibaryon resonances might be comparable to quark configuration mixing, because of the expected smallness of OZI rule violations at those masses.

Nearly "pure" quark states could result. This phenomenon could reveal itself in large violations of isospin and G parity at a single peak and could explain the absence of the $S(1936)$ in $\bar{p}p \rightarrow \bar{n}n$. It should manifest itself most clearly in $\bar{p}n$ and $\bar{n}p$ scattering.

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1. INTRODUCTION

A great deal of interest has recently been focused on the narrow structures coupled preferentially to the baryon-antibaryon system¹⁾.

Several puzzling questions about these states are still awaiting experimental and theoretical clarification. Even if one can expect a rich spectrum of resonances from either the nuclear physics potential approach²⁾ or the dual-quark model viewpoint³⁾⁻⁵⁾, the narrowness of these states and their apparent reluctance to decay into mesons is still largely unexplained. A new selection rule of the Okubo-Zweig-Iizuka (OZI) type seems to be necessary³⁾⁻⁵⁾. The baryonium picture³⁾⁻⁵⁾ appears to give some justification for such a selection rule, in a way which parallels to some extent that of the ordinary OZI rule. The connection is made clearer by the introduction of a colour-gauge theory model⁵⁾ in which possible narrow states are identified with "irreducible" colour singlets which, in an approximation which improves with increasing masses, decay only through the creation of $q\bar{q}$ pairs (i.e., string breaking). If the states that can be reached this way have small zero phase space available, the decaying state will be narrow. In such a picture the S(1936 MeV) bump in $\bar{p}p$ elastic and total cross-sections⁶⁾ is interpreted as a $qq\bar{q}\bar{q}$ state (M_4^J) of $J^{PC} = 3$ (or possibly 2^{++}) with some admixture of $q\bar{q}(M_2^J)$ and quarkless (M_0^J) baryonium in the $I = 1$ and 0 sectors (see below).

In the present paper we take for good the baryonium picture including the $I = 1$ assignment to both the qq and the $\bar{q}\bar{q}$ pair is M_4^J . For more details see Ref. 3). We want instead to address ourselves to another puzzling feature of the S(1936) meson, i.e., the absence of a signal in the charge exchange process $\bar{p}p \rightarrow \bar{n}n$. Existing explanations of this fact rely either on interference of the resonance with background⁷⁾ or an $I = 0, I = 1$ doublet of resonances⁸⁾.

The first explanation requires a very special form for the background which can hardly be understood in the baryonium picture (one would need in $\bar{p}p \rightarrow \bar{n}n$ a purely imaginary background with respect to the resonant part, while the most important source of background in $\bar{p}p \rightarrow \bar{n}n$ is the shadow of "two jet" annihilation which, in the baryonium picture, tends to be real).

The second explanation would imply the existence of two nearly degenerate states with a mass difference of the order of half the width of the S meson, 2-4 MeV, i.e., of the order of a typical electromagnetic mass splitting within an isospin multiplet.

In the light of this observation, we offer here a new and rather unconventional explanation of this phenomenon based on electromagnetic mixing of baryonium states.

2. MIXING OF STATES COUPLED TO $\bar{p}n$ ($\bar{n}p$)

In order to explain the scheme we first consider $\bar{p}n \rightarrow \bar{p}n$ (or $\bar{n}p \rightarrow \bar{n}p$), where the description is somewhat simpler and rather striking phenomena are predicted.

Let us take $\bar{p}n \rightarrow \bar{p}n$. Two $Q = -1$, M_L^J states can appear as intermediate states (see Figs. 1a and 1b) i.e.,

$$|M_U\rangle \equiv |\bar{u}\bar{u}ud\rangle \quad ; \quad |M_D\rangle \equiv |\bar{u}\bar{d}dd\rangle \quad (1)$$

Since (ud) in M_U and $(\bar{u}\bar{d})$ in M_D are taken to be in an $I = 1$ state we have

$$|M_U\rangle = \frac{1}{\sqrt{2}} (|2\rangle + |1\rangle) \quad ; \quad |M_D\rangle = \frac{1}{\sqrt{2}} (|2\rangle - |1\rangle) \quad (2)$$

where $|1\rangle$, $|2\rangle$ are $I = 1, 2$ states. Within the "planar" diagrams of Fig. 1 these two states are degenerate. Their splitting is induced by the diagram of Fig. 2, which shifts intercept of the $I = 1$ trajectory about half a unit above that of the $I = 2$ trajectory⁵⁾. If we denote by δ_{12} the mass splitting $m(I = 2) - m(I = 1)$ at the S mass ($\delta_{12} > 0$), we get, in the M_U, M_D basis a mass matrix of the form

$$\underline{\mathcal{M}}^{(Q=-1)} = \underline{M} \underline{1} + \frac{1}{2} \begin{pmatrix} -\delta_{12} & \delta_{12} \\ \delta_{12} & -\delta_{12} \end{pmatrix} \quad (3)$$

where M is the mass before mixing.

We have to add to this mass matrix the electromagnetic splitting which, we assume, will make M_D heavier than M_U according to the general rule that the d quark is heavier than the u quark.

The complete mass matrix (neglecting widths) is then

$$\underline{M}^{(Q=-1)} = M \underline{1} + \begin{pmatrix} m_d - m_u - 2\epsilon - \frac{\delta_{12}}{2} & \delta_{12}/2 \\ \delta_{12}/2 & 3m_d - 3m_u + \epsilon - \frac{\delta_{12}}{2} \end{pmatrix} \quad (4)$$

$$= \left(M - \frac{7}{2} \epsilon \right) \underline{1} + \begin{pmatrix} \gamma - \delta_{12}/2 & \delta_{12}/2 \\ \delta_{12}/2 & 3\gamma - \delta_{12}/2 \end{pmatrix}$$

where, following Ref. 9), we have separated the contribution coming from the u-d mass difference and that coming from Coulomb interaction energy, $\epsilon > 0$, computed for equidistant quarks. Notice that in the diagonalization of (4) it is only the quantity

$$\gamma = m_d - m_u + \frac{3}{2} \epsilon \quad (5)$$

which enters.

In a standard case $\delta_{12} \gg 4\gamma$ and the matrix (4) is diagonal in the isospin basis. The $I = 1$ resonance will couple to $\bar{p}n$, the $I = 2$ will not.

The question we ask now is whether it is possible to have $\delta_{12} \sim 4\gamma$ or even $\delta_{12} \ll 4\gamma$. Were this the case the isospin basis would no longer be good and the outgoing resonances would not exhibit definite isospin and G parity. In the extreme case, $\delta_{12} \ll 4\gamma$, the quark basis becomes good and peculiar predictions are obtained. Now we turn to some guess-work on the value of δ_{12} . As we said, the expected upward shift of the $I = 1$ baryonium trajectory with respect to the $I = 2$ trajectory, at $M^2 = 0$, is about $\frac{1}{2}$. Furthermore the slopes of the baryonium trajectories at $M^2 = 0$ are expected to obey the approximate relations⁵⁾

$$3\alpha'_{I=0} \approx 2\alpha'_{I=1} \approx \alpha'_{I=2} \approx \alpha'_p$$

indicating that the higher, but flatter, $I = 1$ trajectory will go towards the lower and steeper $I = 2$ trajectory. This is one manifestation of the general

phenomenon of asymptotic planarity¹⁰⁾ of quark states. It can be argued, on the basis of the impact parameter structure of the diagrams of Figs. 1 and 2, that the way the leading trajectories approach each other is indeed exponential in M^2 . If we then try a fit like

$$\Delta\alpha_{12} = \alpha_{I=1}(M^2) - \alpha_{I=2}(M^2) = a e^{-bM^2} \quad (6)$$

to give the right intercepts and slopes we get

$$\Delta\alpha_{12}(M^2) \simeq 1/2 \exp(-\alpha'_\rho M^2) \quad (7)$$

and therefore^{**)}

$$\delta_{12} = \frac{M \cdot \Delta\alpha_{12}}{2\alpha'_\rho M^2} \simeq \frac{M}{4 \times 3.5} e^{-3.5} = 2.15 \cdot 10^{-3} M = 4.2 \text{ MeV} \quad (8)$$

A similar estimate can be tried by comparing our situation with the more familiar one¹⁰⁾ of the f - A_2 splitting. The situation at $M^2 = 0$ is very similar to the one at hand with $\alpha_{I=1}(0) \approx \frac{1}{2}$, $\alpha_{I=0}(0) \approx 1$, $\alpha'_{I=0} \sim \frac{1}{2}\alpha'_{I=1} = \frac{1}{2}\alpha'_\rho$. If we set again $\Delta\alpha_{01} = \frac{1}{2} e^{-\alpha'_\rho M^2}$ we get, for $m_{A_2} - m_f$, 46 MeV to be compared with the experimental value of 40 MeV^{***)}.

From the mass matrix (4) it is easy to check that, if $\gamma/\delta_{12} > 0.75$, the eigenstates are more than 90% pure quark states (i.e., at least of the form

$$\sqrt{.9} |M_\psi\rangle + \sqrt{.1} |M_D\rangle, \sqrt{.9} |M_D\rangle - \sqrt{.1} |M_\psi\rangle).$$

*) A similar argument, when used at fixed J , gives a power behaviour¹¹⁾.

**) The same result is obtained if all our trajectories are displaced down by one unit, thus leading to the assignment $J^{PC} = 2^{++}$ for the $S(1936)$.

***) Such an agreement cannot be obtained by a reasonable power law expression for $\Delta\alpha_{01}(M^2)$.

With $\delta_{12} \approx 4$ MeV it would be enough to have $\gamma > 3$ MeV, a rather small lower bound for producing very pure quark states.

If our interpretation is correct then some very peculiar features should show up in $\bar{p}n$ ($\bar{n}p$) total and elastic cross-sections. One should observe two peaks M_U^- and M_D^- (M_U^+ and M_D^+) with $M_D - M_U$ of the order of an electromagnetic mass difference ($2\gamma \approx 10$ MeV), and more or less equally coupled in the total cross-section. At the peaks one should observe maximal violations of G parity, in particular

$$\Gamma(M_U^- \rightarrow \pi^- + \rho) = \Gamma(M_U^- \rightarrow \pi^- + \omega) \quad (9)$$

$$\Gamma(M_D^- \rightarrow \pi^- + \rho) = \Gamma(M_D^- \rightarrow \pi^- + \omega)$$

Since m_U (m_D) gives only the combination $\rho + \omega$ ($-\rho + \omega$) one should observe a positive (negative) $\rho - \omega$ interference in the three pion mode. Another prediction concerns the $\pi^- e^+ e^-$ for $\pi^- \mu^+ \mu^-$ widths of M_U and M_D . We expect

$$\Gamma(M_U \rightarrow \pi^- l^+ l^-) = 4 \Gamma(M_D \rightarrow \pi^- l^+ l^-)$$

The factor 4 reminds us of the Drell-Yan prediction

$$\Gamma(\pi^- \text{Carbon} \rightarrow l^+ l^- + X) = 4 \Gamma(\pi^+ \text{Carbon} \rightarrow l^+ l^- + X)$$

and indeed the origin of the factor is the same in both cases. There is a crucial difference though. In the Drell-Yan case one expects the ratio to be 1:4 in the continuum, but to become 1:1 at each resonant peak (as it seems to be experimentally observed¹²⁾) whereas we have the 1:4 ratio at a resonant peak.

The experimental situation in $\bar{p}n$ is not very clear. Extracting the $\bar{p}n$ cross-section from $\bar{p}d$ data is rather ambiguous at these low energies. There seems to be some activity near the S region but no indication for two peaks^{*)}. For the ratio of the resonant total cross-sections¹⁴⁾

*) See, however, Ref. 13).

$$R = \frac{\sigma_T(\bar{p}p)}{\sigma_T(\bar{p}p) + \sigma_T(\bar{p}n)} = \frac{(\sigma_0 + \sigma_1)}{(\sigma_0 + 3\sigma_1)} \quad (10)$$

we do not necessarily expect the pure isospin result of either 1 or 1/3, but rather some intermediate value. With reasonable input numbers we get (see below) $R \sim \frac{1}{2}$. We strongly encourage new detailed experiments on deuterium and, if good $\bar{n}$ beams become feasible, measurement of low energy $\bar{n}p$ cross-sections.

3. MIXING OF STATES COUPLED TO $\bar{p}p, \bar{n}n$

We now turn to the $\bar{p}p$ induced processes. The situation here is similar to the one in $\bar{p}n$ except that three $Q = 0$, M_{11}^J quark states come into play

$$|M_{UU}\rangle = |uu\bar{u}\bar{u}\rangle ; |M_{UD}\rangle = |ud\bar{u}\bar{d}\rangle ; |M_{DD}\rangle = |dd\bar{d}\bar{d}\rangle \quad (11)$$

They can be expressed as linear combinations of $I = 0, 1, 2$, states.

In constructing the 3×3 mass matrix we use, for the $I = 1, I = 2$ mass splitting, the parameter δ_{12} as previously defined. A second contribution is now present, coming from the diagram of Fig. 3, which produces only a shift of the $I = 0$ state. We denote by δ_{02} the mass splitting $m(I = 2) - m(I = 0)$. Following again Ref. 9) for the electromagnetic splitting we arrive at the mass matrix

$$\underline{\underline{M}}^{(Q=0)} = (M - 8\epsilon)\underline{\underline{1}} + \begin{pmatrix} 2\gamma - \delta_{02} & -\sqrt{\frac{8}{3}}\gamma & 0 \\ -\sqrt{\frac{8}{3}}\gamma & 2\gamma - \delta_{12} & -\frac{2}{\sqrt{3}}\gamma \\ 0 & -\frac{2}{\sqrt{3}}\gamma & 2\gamma \end{pmatrix} \quad (12a)$$

in the $I = 0, 1, 2$ basis

$$\underline{\underline{M}}^{(Q=0)} = (M - 8\epsilon)\underline{\underline{1}} + \begin{pmatrix} -\frac{1}{3}\delta_{02} - \frac{1}{2}\delta_{12} & -\frac{1}{3}\delta_{02} & -\frac{1}{3}\delta_{02} + \frac{1}{2}\delta_{12} \\ -\frac{1}{3}\delta_{02} & -\frac{1}{3}\delta_{02} + 2\gamma & -\frac{1}{3}\delta_{02} \\ -\frac{1}{3}\delta_{02} + \frac{1}{2}\delta_{12} & -\frac{1}{3}\delta_{02} & -\frac{1}{3}\delta_{02} - \frac{1}{2}\delta_{12} + 4\gamma \end{pmatrix} \quad (12b)$$

in the M_{UU}, M_{UD}, M_{DD} basis

In order to identify the physical states one has to diagonalize the matrix (12). Notice that, again, only the quantity γ of Eq. (5) enters in a non-trivial way. Ratios of cross-sections can be obtained by noticing that the decoupling of $M_{UU}(M_{DD})$ from $n\bar{n}$ ($p\bar{p}$) implies a certain value for the ratio of the $B\bar{B}$ couplings to $I = 0$ and $I = 1$ M_4^J states, i.e.,

$$(B\bar{B}M_4^J)_{I=0} = \sqrt{\frac{3}{2}} (B\bar{B}M_4^J)_{I=1} \quad (13)$$

A numerical exploration shows that, within a reasonable range of the parameters, the lowest state, identified with the S(1936), couples to $p\bar{p}$ elastic and total cross-sections much more (by one or two orders of magnitude) than the other two. The same peak is the one which is most coupled to $p\bar{p} \rightarrow n\bar{n}$. Phenomenologically it is interesting to consider the ratio of elastic and charge exchange cross-sections at this peak.

Our results are summarized in Fig. 4 where we give, as a function of $x = \delta_{12}/\delta_{02}$ is the interval $0 \leq x \leq 0.8$, the critical value of γ/δ_{02} above which the peak cross-sections over the background are in the ratio^{*)}

$$\sigma(\bar{p}p \rightarrow \bar{n}n) / \sigma(\bar{p}p \rightarrow \bar{p}p) < 0.07$$

This value is an upper limit obtained by Eisenhandler¹⁵⁾ from the data of Refs. 6) and 16). At about the same γ_{crit} the S(1936) becomes more than 90% $\bar{u}u$, and this is why it becomes so little coupled to $p\bar{p} \rightarrow n\bar{n}$.

The value of δ_{12}/δ_{02} is not so easy to predict. If one uses again an exponential form to fit

$$\alpha_{I=0}(0) - \alpha_{I=2}(0) = 1.0$$

and

$$\alpha_{I=0}^I(0) \approx \frac{1}{3} \alpha_{I=2}^I(0)$$

which corresponds to considering mixing of M_4^J, M_2^J, M_0^J states at all M^2 , one gets $\delta_{12}/\delta_{02} \approx 0.14$.

*) Notice that our calculated value does not include any possible effect from interfering background.

Using this number, we get from Fig. 4 $\gamma_{\text{crit}}/\delta_{02} \approx \frac{1}{2}$. If one takes $\delta_{12} = 4$ MeV and $\delta_{02} \approx 28$ MeV, one obtains $\gamma_{\text{crit}} \approx 14$ MeV which is not an inconceivable electromagnetic mass splitting.

On the other hand it seems more natural to argue that, at the S mass, only the three $Q = 0$ M_h^J states we have considered, mix together. In this case a not completely trivial calculation gives $\delta_{12}/\delta_{02} = 2/3$. From Fig. 4 we get $\gamma_{\text{crit}}/\delta_{02} \approx 1/3$, i.e., $\gamma_{\text{crit}} \approx 2$ MeV for $\delta_{12} = 4$ MeV. We see that, even by making δ_{12} 10 or 15 MeV, we still get values of γ_{crit} in an acceptable range (one expects $m_d - m_u \approx 5$ MeV⁹⁾ and $\epsilon \approx 10^{-3}$ $\langle 1/r \rangle \approx 0.5$ MeV, hence $\gamma \approx 6$ MeV but these values could be somewhat mass dependent).

The integrated $\bar{p}p$ total cross-section at the S peak turns out to be close to the sum of the integrated $\bar{p}n$ (or $\bar{n}p$) total cross-sections over the two peaks M_U, M_D . For $\gamma > \gamma_{\text{crit}}$ these peaks are about $m_d - m_u + 6\epsilon$ (~ 10 MeV) and $3(m_d - m_u) + 9\epsilon$ (~ 20 MeV) above the $S(1936)$, respectively.

Again we expect violations of isospin and G parity at the peak. In particular, if $\gamma > \gamma_{\text{crit}}$,

$$\Gamma(S \rightarrow \rho^0 \rho^0) \approx \Gamma(S \rightarrow \rho^0 \omega) \approx \Gamma(S \rightarrow \omega \omega)$$

with positive ρ - ω interference in the 4π mode.

4. CONCLUSIONS

We conclude this admittedly speculative paper by stressing that baryonium could be the unique system allowing for the electromagnetic mixing effects described above to reveal themselves (if not in the case of the S , perhaps in other members of the baryonium family). This is because one needs narrow high mass mesons in order to suppress OZI rule violations and at least a $\bar{u}u$ (or $\bar{d}d$, $\bar{u}d$, $\bar{d}u$) pair of quarks. This restricts us to look for particles with some selection rule against their decay into light mesons and leads us naturally into the family of exotic hadrons of the $qq\bar{q}\bar{q}$, $qqqq\bar{q}\bar{q}$... kind including, of course, states such as $s\bar{s}u\bar{u}$, $c\bar{c}u\bar{u}$ and similar ones.

We wish to thank R. Bizzarri and C.B. Dover for discussions.

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FIGURE CAPTIONS

- Figure 1 : Leading diagrams contributing to $\bar{p}n \rightarrow \bar{p}n$ scattering showing:
 a) the $|M_U\rangle$ intermediate state, and
 b) the $|M_D\rangle$ intermediate state.
- Figure 2 : The two-jet Zweig violating scattering diagram responsible for shifting $I = 0$ and $I = 1$ baryonium states.
- Figure 3 : The three-jet Zweig violating scattering diagram responsible for further shifting of $I = 0$ baryonium states.
- Figure 4 : The critical value of γ/δ_{02} at which

$$\frac{\sigma(p\bar{p} \rightarrow p\bar{p})}{\sigma(p\bar{p} \rightarrow n\bar{n})} \Big|_{S_{\text{peak}}} < 0.07$$

as a function of the ratio between the $(I = 1, I = 2)$ mass splitting δ_{12} and the $(I = 0, I = 2)$ mass splitting δ_{02} .

FIG. 1

FIG. 2

FIG. 3

FIG. 4