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QUASINUCLEAR $N\overline{N}$ STATES

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ABSTRACT

We present an interpretation of recent experimental results on nucleon–anti-nucleon annihilation reactions of the type $N\overline{N} \to \pi X$, which have yielded evidence for a new tensor meson AX (here called X_2) with $J^{\pi C}(I^G) = 2^{++}(0^+)$. The branching ratios for producing X_2 from $N\overline{N}$ atomic states of orbital angular momentum $L = 0, 1$, as well as its preference for decay into $\rho\rho$ and $\pi\pi$ rather than $K\overline{K}$ channels, are consistent with the identification of X_2 as a $^{13}\mathrm{P}_2$–$^{13}\mathrm{F}_2$ bound state of the $N\overline{N}$ potential. We suggest further key tests of this interpretation.

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We present an interpretation of recent experimental results on nucleon–antinucleon annihilation reactions of the type $N\overline{N} \to \pi X$, which have yielded evidence for a new tensor meson AX (here called X_2) with $J^{\pi C}(I^G) = 2^{++}(0^+)$. The branching ratios for producing X_2 from $N\overline{N}$ atomic states of orbital angular momentum $L = 0, 1$, as well as its preference for decay into $\rho\rho$ and $\pi\pi$ rather than $K\overline{K}$ channels, are consistent with the identification of X_2 as a $^{13}P_2$–$^{13}F_2$ bound state of the $N\overline{N}$ potential. We suggest further key tests of this interpretation.

1. INTRODUCTION

The nucleon–antinucleon ($N\overline{N}$) annihilation process affords a promising means of searching for new mesonic species which lie beyond the well established SU(3) nonets of quark–antiquark ($Q\overline{Q}$) states. These new configurations might include four quark ($Q^2\overline{Q}^2$) states, hybrid mesons ($Q\overline{Q}g$) involving an excited mode g of the gluon field, or glueballs. There is also the possibility of quasinuclear (QN) bound states of the $N\overline{N}$ system[1–5], somewhat analogous to the $K\overline{K}$ "molecules" which have been invoked to explain the puzzling features of scalar (1^{++}) mesons in the 1 GeV region[6].

In this paper, we present arguments to support the contention that a new tensor meson state X_2, seen in the reaction $N\overline{N} \to \pi X_2$, may be interpreted as a tensor coupled $^{2I+1,2S+1}L_J = {}^{13}P_2$–$^{13}F_2$ bound state of the $N\overline{N}$ system. Our identification has several facets: consistency of quantum numbers, production branching ratio, and relative strength of decay modes. Assuming that the quasinuclear interpretation is valid, we discuss several other predictions of the model, and compare them with a more conventional multi–quark plus gluon description.

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2. RESUMÉ OF THE DATA

In bubble chamber experiments at the Brookhaven AGS, Gray *et al.*[7] saw evidence for a peak in the $\pi^+\pi^-$ and $\pi^0\pi^0$ mass spectra near 1530 MeV, in studies of $\bar{p}n \to 2\pi^-\pi^+$ and $\bar{p}p \to 3\pi^0$ annihilation. In a later AGS experiment, Bridges *et al.*[8] identified a peak in the $2\pi^+2\pi^-$ system near the same mass in $\bar{p}n \to 3\pi^-2\pi^+$; the quasi–two-body reaction chain $\bar{p}n \to \pi^- X_2$, $X_2 \to \rho^0\rho^0$ was proposed, with a quantum number assignment $J^{\pi C}(I^G) = 2^{++}(0^+)$ for X_2. The existence of a peak in the $2\pi^+2\pi^-$ mass spectrum around 1500 MeV was confirmed[9] by the ASTERIX group at LEAR. More recently, the ASTERIX collaboration[10] investigated the $p\bar{p} \to \pi^0\pi^+\pi^-$ reaction initiated from an $L = 1$ atomic state. They found a peak in the $\pi^+\pi^-$ mass spectrum at 1565 MeV. This object, dubbed the AX(1565), is a $2^{++}(0^+)$ state. The Crystal Barrel collaboration[11] at LEAR has recently studied $p\bar{p} \to 3\pi^0$, and seen a $\pi^0\pi^0$ structure at 1515 MeV, with quantum numbers $2^{++}(0^+)$. Amsler[12] has beautifully summarized the evidence for the $AX = X_2(2^{++}(0^+))$ meson, and reported preliminary indications in the $p\bar{p} \to \pi^0\eta\eta$ channel for a peak in the $\eta\eta$ invariant mass near 1500–1550 MeV.

As a working hypothesis, we assume[4,5] that the structures observed in the $\pi\pi$ channel by Gray *et al.*[7], May *et al.*[10], Aker *et al.*[11] and the $\rho^0\rho^0$ state seen by Bridges *et al.*[8] and Ahmad *et al.*[9] correspond to the same object, observed in two different decay channels. Then the decay $X_2 \to \rho\rho$ is found to be significantly larger than $X_2 \to \pi\pi$, which in turn dominates $X_2 \to K\bar{K}$, for which only an upper limit exists[7].

The SU(3) nonet of $2^{++}(0^+)$ mesons is already fully occupied by the $a_2^{\pm,0}(1320)$, $f_2(1270)$, $f_2'(1525)$ and $K_2^*(1430)$. Thus the existence of an additional $2^{++}(0^+)$ state, the AX, is either disturbing or exhilarating, depending on one's viewpoint. In any case, the AX presents us with a challenge: what is its nature?

3. SPECTRUM OF $N\bar{N}$ BOUND STATES

The general features of the spectrum of $N\bar{N}$ bound states has been often discussed[1–3,13–14]. Given a meson exchange model for the nucleon–nucleon (NN) potential V_{NN}, the $N\bar{N}$ potential $V_{N\bar{N}}$ may be obtained via the transformation:

$$V_{NN} = \sum_i V_i, \quad V_{N\bar{N}} = \sum_i G_i V_i \tag{1}$$

where G_i is the G-parity of meson i, and

$$\begin{aligned} V_i =& V_c + \sigma_1 \cdot \sigma_2 V_\sigma + L \cdot S V_{LS} + S_{12} V_T \\ S_{12} =& 3\sigma_1 \cdot \hat{r}\, \sigma_2 \cdot \hat{r} - \sigma_1 \cdot \sigma_2 \end{aligned} \tag{2}$$

The real potential $V_{N\bar{N}}$ must be supplemented by an annihilation potential $V_{\rm ann}$ in order to fit the low energy $N\bar{N}$ data. The key notion in understanding the level order of the spectrum of $N\bar{N}$ bound and resonant states is the *coherence* of different components of the meson exchange potentials in specified quantum states ${}^{2I+1,2S+1}L_J$ (I = isospin, S = intrinsic spin, L = orbital angular momentum (not in general a good quantum number because of tensor mixing), and J = total angular momentum). In the NN system, $\sigma_1 \cdot \sigma_2$ and $L \cdot S$ potentials are coherent (same sign) for $S = 1$, $I = 1$ states, while for $N\bar{N}$, central and tensor (S_{12}) terms are coherent[2,15] and attractive for $I = 0$, $S = 1$. The tensor contributions lead to very strong mixing[15] of $L = J \pm 1$ states for $S = 1$, unlike the situation for the deuteron. The wave functions ψ_J of tensor–coupled $N\bar{N}$ bound states are close to the linear combination[15]

$$|\psi_J\rangle = (2J+1)^{-1/2}\left[(J+1)^{1/2}|L = J+1\rangle - J^{1/2}|L = J-1\rangle\right] \qquad (3)$$

which diagonalizes S_{12}. For $|\psi_J\rangle$, the centrifugal term in the Schrödinger equation has the form $(J^2+J+2)/Mr^2$, corresponding to an effective orbital angular momentum $L_{\text{eff}} = 1.6$, 2.4 and 3.3, respectively, for $J = 1, 2$, and 3. This substantial angular momentum barrier inhibits the wave function from penetrating to short distances and prevents the annihilation width from becoming too large. For a weak tensor force, on the other hand, the $L = J - 1$ configurations would dominate, and $L_{\text{eff}} = 0, 1$ for ${}^{13}S_1$, ${}^{13}P_2$, etc; the resulting bound states, now supported mostly by the attractive central potential, may become unobservably broad. This is also true for $I = 1$ or $S = 0$ bound states, for which the coherent tensor force is not operative. Thus, if the tensor potential is strong, the $N\bar{N}$ spectrum assumes a rather simple form, consisting of an $I = 0$, $S = 1$ natural parity band

$$\begin{aligned} &0^{++}(0^+)\left[{}^{13}P_0\right], 1^{--}(0^-)\left[{}^{13}S_1 - {}^{13}D_1\right], \\ &2^{++}(0^+)\left[{}^{13}P_2 - {}^{13}F_2\right], 3^{--}(0^-)\left[{}^{13}D_3 - {}^{13}G_3\right]\ldots \end{aligned} \qquad (4)$$

accompanied possibly by a few $I = 1$, $L = 1$ states close the the $N\bar{N}$ threshold. However, most of the plethora of $N\bar{N}$ states predicted in early calculations[1,2] are expected to be extremely broad, particularly if they rely exclusively on short range central attraction for their binding. Thus the observable part of the $N\bar{N}$ spectrum is likely to be rather sparse; even the lower spin 0^{++} and 1^{--} members of the band (4) may be too broad to be observable, since they are predicted far below threshold. Our focus here is on the higher spin states 2^{++} and 3^{--}: in various calculations[1,2 ,13–16], the $2^{++}(0^+)$ state was found in the mass range 1500–1600 MeV, close to the observed position of the X_2. A typical hadronic width of order $\Gamma \approx 100$–200 MeV is expected for the $2^{++}(0^+)$ state[4,5,14,16], whereas configurations bound only by central attraction (${}^1S_0$, ${}^1P_1$ etc.) probably have $\Gamma > 300$ MeV.

4. PRODUCTION BRANCHING RATIOS

The measured product of branching ratios B given by May *et al.*[10] is

$$B\left(p\bar{p}(L=1) \to \pi^0 X_2\right) \cdot B\left(X_2 \to \pi\pi\right) = (5.6 \pm 0.9) \times 10^{-3} \quad (5)$$

This is in agreement with the prediction[3,5] of 6×10^{-3}, based on the interpretation of X_2 as the ${}^{13}P_2$–${}^{13}F_2$ QN bound state[4,5]. The two factors in Eq. (5) are

$$B\left(N\overline{N}(L=1) \to \pi^0 X_2\right) \approx 3 \times 10^{-2} \quad (6a)$$

$$B\left(X_2 \to \pi\pi\right) \approx 0.2 \quad (6b)$$

Eq. (6a) includes the effect of $p\bar{p} - n\bar{n}$ isospin mixing[3](the value is 5×10^{-2} with pure $p\bar{p}$); Eq. (6b) will be justified in the next section. The situation for $L = 0$ is less clear, since the B values extracted from $\bar{p}n \to \pi^- X_2$ and $p\bar{p} \to \pi^0 X_2$ measurements do not agree very well (see Ref. (5) for details). Nevertheless, it appears that

$$B\left(N\overline{N}(L=0) \to \pi^0 X_2\right) / B\left(N\overline{N}(L=1) \to \pi^0 X_2\right) < 1/3 \quad (7)$$

which is consistent with the expected suppression of $L = 0$ production, attributed to kinematical effects ($L = 0 \to \pi X_2(\ell = 2)$ suppressed relative to $L = 1 \to \pi X_2(\ell = 1)$) and destructive interference due to $p\bar{p} - n\bar{n}$ mixing[3,5].

5. DECAY MODES OF $N\overline{N}$ BOUND STATES

The energetically allowed two–body decay modes of the X_2 are

$$\begin{aligned} X_2\left(2^{++}(0^+)\right) \to & \pi\pi\,(\ell=2)\,,\ \eta\eta\,(\ell=2)\,,\ \rho\rho\,(\ell=0,2)\,, \\ & \omega\omega\,(\ell=0,2)\,,\ \pi a_1\,(\ell=1,3)\,,\ \pi a_2\,(\ell=1,3)\,, \\ & K\overline{K}\,(\ell=2)\,,\ K\overline{K}^*\,(\ell=2) \end{aligned} \quad (8)$$

To estimate the relative branching ratios[5], the planar annihilation topology[17,18] of the quark model was chosen, with vacuum quantum numbers for the effective $Q\overline{Q}$ annihilation/creation operators (the ${}^3P_0$ model). The widths Γ for each decay $X_2 \to M_i M_j$ are of the form

$$\Gamma\left(X_2 \to M_i M_j\right) = F_\ell(q)\,(SF)_{ij} \quad (9)$$

where q is the meson c.m. momentum, $F_\ell(q)$ is a kinematical form factor, and $(SF)_{ij}$ are spin–flavor weights tabulated in Refs. (5,18). The results of this calculation[5] are displayed in Fig. 1. The dominant decay mode is predicted to be $X_2 \to \rho\rho$, followed by $\pi\pi$ and a number of less important channels. The strange particle decay modes of X_2 are expected to be small, consistent with the observed strong suppression of $N\overline{N}(L = 1) \to K\overline{K}$ transitions[19] and the limit $B(X_2 \to K\overline{K})/B(X_2 \to \pi\pi) < 1/16$ obtained by Gray *et al.*[7]. If the structure seen by Bridges *et al.*[8] in the $\rho^0\rho^0$ channel and the state seen by ASTERIX[10]

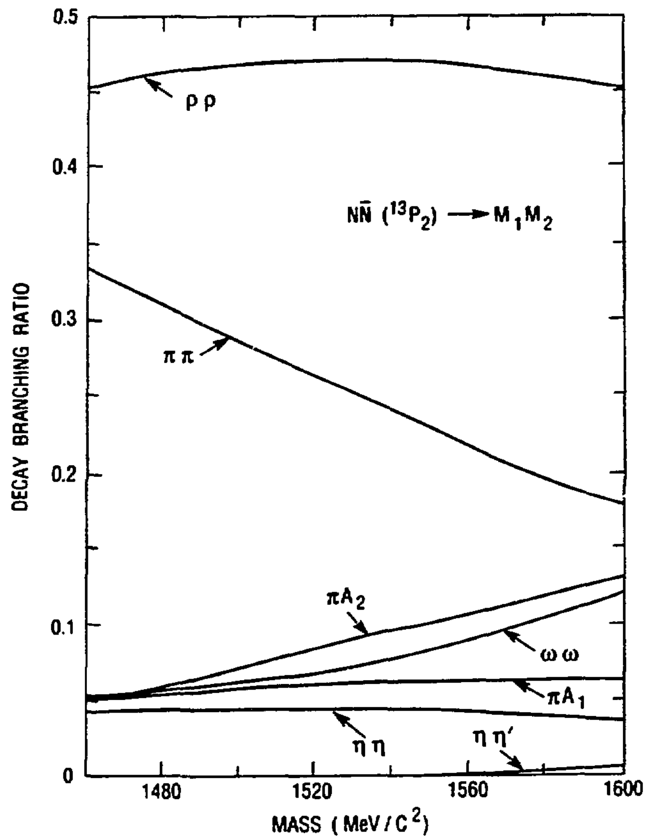

Figure 1: Predicted branching ratios[5] for the decay of the quasinuclear state $X_2[2^{++}(0^+)]$ into two meson final states, as a function of its mass.

and Crystal Barrel[11] in the $\pi\pi$ system are taken to be the same $2^{++}(0^+)$ object, then the large value $B(\bar{p}n \to \pi^- X_2) \cdot B(X_2 \to \rho^0\rho^0) \approx 3.7 \times 10^{-2}$ given by Bridges *et al.*[8] implies

$$B(X_2 \to \rho\rho) \gg B(X_2 \to \pi\pi), \tag{10}$$

consistent with the estimates in Fig. 1.

6. OTHER INTERPRETATIONS

As we have argued above, the observed quantum numbers, mass, width, and production and decay branching ratios of the X_2 are consistent with its interpretation as a $^{13}P_2$–$^{13}F_2$ quasinuclear $N\bar{N}$ state. The binding energy of this state is a modest fraction ($\sim 1/6$) of the threshold $N\bar{N}$ mass, so the notion of a QN state is reasonable. Just as for the $\Delta(1230)$, where one has complementary physical pictures, in terms of a p-wave πN resonance in the hadronic basis and as a Q^3 state in the quark picture, one is invited to search for a clear and decisive interpretation of the X_2 in the underlying quark–gluon representation. We examine some of the possibilities here:

A) Is X_2 a $Q\overline{Q}$ state? No. The radial excitation of the $f_2(1270)$ is expected[20] at 1820 MeV, well above the X_2. The X_2 is not observed to decay into $K\overline{K}$, so it cannot be identified with the $s\bar{s}$ state $f_2'(1525)$, which decays predominantly to $K\overline{K}$.

B) Is X_2 a glueball? Probably not. There is no good reason why a glueball should not decay into $K\overline{K}$, but X_2 does not. If X_2 were a glueball, it should be seen in J/ψ radiative decays, but there is no sign of it. Finally, lattice gauge calculations predict a 2^{++} to 0^{++} mass ratio of about 1.5, so 2^{++} glueballs as low as 1.5 GeV are unlikely.

C) Is X_2 a $Q\overline{Q}g$ hybrid? Probably not. No $2^{++}(0^+)$ hybrid states are predicted below 2 GeV, in any existing model.

D) Is X_2 a $Q^2\overline{Q}^2$ state? This is not ruled out. Suppose one starts with diquarks α and β of SU(3) color $\{\bar{3}\}$ and $(S,I) = (0,0)$ or (1,1), respectively. Jaffe[21] has estimated the masses of states on three trajectories $A = \alpha\bar{\alpha}$, $B^\pm = \alpha\bar{\beta} \pm \bar{\alpha}\beta$, $C = \beta\bar{\beta}$. Trajectory A has the same quantum numbers as the quasinuclear states of Eq. (4), and couples strongly to the $N\overline{N}$ channel. However, the $2^{++}(0^+)$ member of trajectory A is predicted near 1950 MeV, above the $N\overline{N}$ threshold, and far above the X_2 mass. Such a configuration could be admixed in the X_2 wave function to some degree. Trajectory C provides a $2^{++}(0^+)$ state at about 1550 MeV, close to the X_2, but this is accompanied by $2^{++}(1^-, 2^+)$ partners, for which there is no evidence in the $N\overline{N}$ data. A $2^{++}(2^+)$ meson would appear in the $\rho^\pm\rho^\pm$ and $\pi^\pm\pi^\pm$ channels; the latter seems to be ruled out on the basis of the $\bar{p}n \to 2\pi^-\pi^+$ data[7].

E) Is the X_2 something else? Be my guest.

7. KEY TESTS OF THE QUASINUCLEAR PICTURE

The observable ($\Gamma < 200$ MeV) part of the $N\overline{N}$ bound state spectrum is likely to be rather sparse. The coherent tensor potential, from π, η, ρ, ω exchanges, operates only for $I = 0$, $S = 1$ states, and produces large isospin splittings. In the quark model, tensor forces also occur in the one gluon exchange approximation, but they are much weaker than in meson exchange theories, and do not lead to large breaking of isospin degeneracy.

We have focused our attention on one particular state, the $X_2\,(2^{++}(0^+))$. However, the $N\overline{N}$ model predicts the natural parity $I = 0$ band on Eq. (4). Hints of structures in the $0^{++}(0^+)$ and $1^{--}(0^-)$ channels are discussed in Ref. 5. However, these states, if they exist, correspond to substantial binding energies (about 800 and 600 MeV, respectively), so their interpretation as quasi–molecular structures may be dubious. Surely, the non–relativistic picture, employed to estimate their binding energies, may be called into question. The ${}^{13}D_3$–${}^{13}G_3[3^{--}(0^-)]\,N\overline{N}$ configuration X_3, on the other hand, is predicted[1,2,13] to be more weakly bound than the X_2, so it qualifies as an excellent candidate for a QN state. It is likely to lie in the mass region above 1700 MeV, so it is probably not accessible via the $N\overline{N} \to \pi X_3$ reaction. Transitions $N\overline{N}(L = 0) \to \gamma X_3$

are strongly suppressed, since they cannot proceed via E1 or M1 radiation. On the other hand, from $L = 1$, we have $N\bar{N}(^{13}P_2 - {}^{33}P_2) \rightarrow \gamma X_3(\ell = 1)$, which is a favored E1 transition. Since X_3 and other QN states are rather broad ($\Gamma > 100$ MeV), studies of the inclusive γ spectrum are unlikely to reveal their existence. The γ must be detected in coincidence with the decay products of X_3. Allowed decay channels include $X_3 \rightarrow \pi b_1(1235)$ with $\ell = 2$ and $X_3 \rightarrow \pi\rho(\ell = 3)$. For the latter, the relevant channel is $p\bar{p} \rightarrow \gamma + \pi^0\pi^+\pi^-$. If other members of the $I = 0$ $N\bar{N}$ band are found, the quasinuclear interpretation of the $X_2[2^{++}(0^+)]$ meson presented here may have to be taken seriously.

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