Have Quasinuclear $N\bar{N}$ Bound States Been Discovered?

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It is suggested that a broad structure $X^0(1480)$ recently observed in the reaction $\bar{p}n \to \pi^- X^0 \to 3\pi^-2\pi^+$ may be interpretable in terms of an unstable quasinuclear bound state of the (complex) nucleon-antinucleon ($N\bar{N}$) potential. The observed mass, production branching ratio, and preference for the $X^0 \to \rho^0\rho^0$ rather than $\pi^+\pi^-$ decay mode are consistent with a quantum-number assignment $J^{PC}(I^G) = 2^{++}(0^+)$. Prospects for finding the lower-lying $0^{++}(0^+)$ and $1^{--}(0^-)$ members of the expected natural-parity quasinuclear band are discussed.

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It has long been recognized that the $N\bar{N}$ system offers in principle an ideal entrance channel for the production of new types of mesons, in addition to the usual quark-antiquark ($Q\bar{Q}$) configurations. These new mesons could include, for instance, quasinuclear (QN) bound states of the $N\bar{N}$ potential,[1] "baryonium" states of $Q^2\bar{Q}^2$ structure,[2] "hybrids," i.e., $Q\bar{Q}g$ mesons[3] containing a dynamical gluon g, or glueballs.[4] The search for new *narrow* mesons coupled to the $N\bar{N}$ system has been intense, but earlier evidence for the existence of such objects has not been confirmed in recent experiments[5] with intense $\bar{p}$ beams at LEAR (Low Energy Antiproton Ring at CERN).

Unless there is a topological selection rule[6] suppressing direct decay of "baryonium" into mesons, one generally expects broad states. For instance, for $N\bar{N}$ quasinuclear mesons, the typical scale of width[1] is $\Gamma \approx 100$ MeV, although narrower structures may occur in particular cases.[7,8] New mesons, if they are highly unstable, are generally difficult to extract in a convincing way from $N\bar{N}$ annihilation data. Even if one picks a particular pion multiplicity n, there will often be numerous quasi two-body (QTB) reactions $N\bar{N} \to M_1M_2$, leading directly to ordinary $s = \{\pi, \eta, \rho, \omega\}$ and $p = \{\epsilon, \delta, A_1, A_2, D, f, B, H\}$ mesons M_1 and M_2. This "background" of QTB modes, interesting in its own right because of the connection between the underlying quark-gluon dynamics and observed selection rules,[9] masks the production of new mesons X in reactions such as $N\bar{N} \to \pi X$ or γX.

To minimize the QTB and other backgrounds, one can choose the initial $N\bar{N}$ state and the particular final pion charge states in an optimum way. For instance, the $\bar{p}n$ or $\bar{n}p$ initial states are more favorable in this regard than $\bar{p}p$, since we thereby restrict attention to entrance channel isospin $I = 1$, and thus eliminate $I = 0$ QTB modes. If we then choose n even or odd, i.e., G parity $= (-)^n$, we select ${}^{2I+1,2S+1}L_J = {}^{33}S_1$ or ${}^{31}S_0$ initial $N\bar{N}$ states, respectively. We here assume that annihilation takes place from $L = 0$ states. Finally, we focus on annihilation modes containing the *minimum* number of π^0's, since these contain the fewest QTB configurations. By explicit enumeration of QTB modes for each n, we have found that *the reaction* $\bar{p}n \to 3\pi^-2\pi^+$ *is optimal for the study of new mesons* X^0 *via the process* $\bar{p}n \to \pi^- X^0$. Note that X^0 can have isospin 0, 1, or 2. On the other hand, $\bar{p}p \to \pi^\pm X^\mp$ can only be used to produce isovector or isotensor mesons X, so that the expected deeply bound isoscalar $N\bar{N}$ states[1] will not be seen.

The reactions

$$\bar{p}d \to p_s + (\bar{p}n), \quad (\bar{p}n) \to \pi^- X^0, \quad X^0 \to \pi^+\pi^-, \pi^+\pi^-\pi^0, 2\pi^+2\pi^- \tag{1}$$

were recently studied by Bridges *et al.*[10] A cut was made on the momentum of the recoiling proton p_s to separate out the "spectator" events. For each multiplicity, they form the *difference spectrum* $N(\pi^-) - N(\pi^+)$, where $N(\pi^\pm)$ is the number of events corresponding to inclusive $\pi^\pm$ production. This helps to separate the "primary" π^- produced via $\bar{p}n \to \pi^- X^0$ from the background of π^-'s arising from the decays of X^0 or other neutral mesons. (These produce the same π^+ and π^- spectra by C invariance.) Note that the difference technique does not totally eliminate contributions from modes $\bar{p}n \to M_1^- M_2^0$, if $M_1^- \neq \pi^-$, but such modes do not produce sharp peaking in the missing mass recoiling against a π^-. For $\bar{p}n \to 2\pi^-\pi^+$ and $3\pi^-2\pi^+$, respectively, the only QTB modes which conserve $J^{PC}(I^G)$, starting from the ${}^{31}S_0$ initial state, are

$$\bar{p}n \to \pi^-\rho^0\ (l_f=1),\ \pi^-\epsilon\ (l_f=0),\ \pi^-f\ (l_f=2) \to \rho^0A_1^-\ (l_f=0,2),\ \rho^0A_2^-\ (l_f=2), \tag{2}$$

where l_f is the meson-meson relative orbital angular momentum. Note that $\rho^0A_2^-$ will be strongly suppressed because $l_f = 2$, and the available phase space is small. For $\bar{p}n \to 2\pi^-\pi^+\pi^0$, numerous QTB modes contribute, and hence this channel is not as favorable for isolation of a new X^0.

Bridges *et al.*[10] have noticed a broad structure $X^0(1480)$ in the difference spectrum for $\bar{p}n \rightarrow 3\pi^- 2\pi^+$. They were not able to explain it in conventional terms as a QTB or three-body process. They find a mass value $M_0 = 1477 \pm 5$ MeV, a width $\Gamma = 116 \pm 9$ MeV, a dominant decay mode $X^0(1480) \rightarrow \rho^0\rho^0$, and a product branching ratio

$$B(\bar{p}n \rightarrow \pi^- X^0(1480)) B(X^0(1480) \rightarrow \rho^0\rho^0) \approx 3.5\%.$$

A quantum-number assignment $J^{PC}(I^G) = 2^{++}(0^+)$ is suggested[11] for the $X^0(1480)$. In this paper, we offer a plausible *interpretation of the* $X^0(1480)$ *as the* $^{13}P_2$-$^{13}F_2$ *QN bound state of the* $N\bar{N}$ *system.* It is argued that the observed mass, width, decay modes and production branching ratio for $X^0(1480)$ are reasonable in the context of an $N\bar{N}$ potential model, although an explanation in terms of the complicated dynamics of the 5π system or final-state interactions ($\rho\rho$ *s*-wave rescattering, for instance) may also be possible.

Theoretical spectra of $N\bar{N}$ bound states have been obtained by numerous authors.[1,2,7,8] Although the absolute binding energies are very sensitive to the details of the short-range interaction, certain features of the level ordering are preserved for a wide class of one-boson-exchange potentials. As a result of the *coherent tensor potentials* arising from π, ρ, and ω exchange, the lowest-lying levels of a given J form an $I=0$ *natural-parity band,* with quantum numbers $0^{++}(0^+)$, $1^{--}(0^-)$, $2^{++}(0^+)$, etc. The wave functions for these states are very close to the coherent mixture[12]

$$|\beta_J\rangle = [-J^{1/2}|L=J-1\rangle + (J+1)^{1/2}|L=J+1\rangle]/(2J+1)^{1/2} \quad (3)$$

which diagonalizes the tensor operator S_{12}. For $|\beta_J\rangle$, the same tensor potential operates for all J, so that the main mechanism for mass splitting ΔM is the centrifugal term $(J^2+J+2)/M_N r^2$ in the effective potential. This gives the approximate relation

$$\Delta M(2^+ - 1^-) \approx 2\Delta M(1^- - 0^+). \quad (4)$$

Annihilation will modify Eq. (4), but not in a qualitative way, according to the calculations of Niskanen and Green[7] and Lacombe *et al.*[8] If $X^0(1480)$ is identified as the 2^+ state, then we anticipate the 1^- and 0^+ states in the mass range 1100–1400 MeV/c^2. These will be more difficult to isolate: The 1^- lies in the same mass region as ordinary p mesons, and separating πX^0 from πA_2, for instance, since $X^0(1^-)$ and A_2 have the same preferred $\pi\rho$ decay mode, would require a careful multichannel amplitude analysis. Some evidence for a broad structure near 1100 MeV/c^2, decaying into $\pi^+\pi^-$, and produced in the reaction $\bar{p}n \rightarrow \rho^- X(1100)$, has been given by Daftari *et al.*[13] If confirmed, this could be a candidate for a $0^{++}(0^+)$ state.

The $Q^2\bar{Q}^2$ spectrum calculated by Jaffe[2] also displays a 0^{++}, 1^{--}, 2^{++}, etc., natural-parity band with $I=0$, which enjoys maximal coupling to the $N\bar{N}$ channel. However, the 2^{++} state is predicted to lie around 1960 MeV/c^2, above the $N\bar{N}$ threshold, and rather far from the $X(1480)$. Possible 2^{++} glueball[14] and hybrid[3] states also lie at higher mass. For $N\bar{N}$ potential models, on the other hand, the $2^{++}(I=0)$ state usually lies far below the $N\bar{N}$ threshold[1,7,8] in the region of $X^0(1480)$, a consequence of the very strong and attractive tensor force.[1,12]

The production branching ratios of $N\bar{N}$ QN states X in the reactions $(p\bar{p})_{\text{atom}} \rightarrow \pi^\pm X^\mp$, $\pi^0 X^0$, and γX^0 were estimated by Dover, Richard, and Zabek.[15] The results depend sensitively on the match between l_F and the available momentum q in the final state, as well as the isospin mixing in the $p\bar{p}$ atom. If we scale the results of Ref. 15 to the correct q, using a modified penetrability $(qR)^{l_F}\exp(-R^2q^2/4)$, we estimate branching ratios of 1%–10%, relative to the total annihilation, for the process $\bar{p}n \rightarrow \pi^- X^0(1480)$. This is comparable to the observed rate. Such branching ratios may seem large, but calculations[15,16] show that the $N\bar{N}$ atom finds it rather easy to emit a single pion and collapse to a QN $N\bar{N}$ state with tighter radial localization but the same quark content.

The final key point concerns the mesonic decay modes of the QN $N\bar{N}$ states. These are expected to follow the decay pattern of $N\bar{N}$ atomic states, except that the available energy has been reduced from $2m_N$. That is, strange-particle decay modes, such as $K\bar{K}$ or $K^*\bar{K}$, will be relatively rare, since the QN states, unlike the ϕ or f' mesons, for instance, have only small strange-quark admixtures. The nonstrange QTB decay modes available to the $2^{++}(0^+)$ meson $X^0(1480)$ are

$$X^0(1480) \rightarrow \begin{cases} \pi^0\pi^0,\ \pi^+\pi^-,\ \eta\eta\ (l_f=2), \\ \rho^0\rho^0,\ \rho^+\rho^-,\ \omega\omega\ (l_f=0,2), \\ \pi^0 A_1^0,\ \pi^\pm A_1^\mp\ (l_f=1,3). \end{cases} \quad (5)$$

The πA_1 ($l_f=1$) modes will be kinematically suppressed, whereas the $\eta\eta$ and $\omega\omega$ modes contribute to $\bar{p}n \rightarrow \pi^- X^0$ annihilation channels of multiplicity seven containing two π^0's, which have not been isolated experimentally. The decay mode $X^0(1480) \rightarrow \pi^+\pi^-$ should have been seen, however. *We propose that the*

$X^0(1480)$ and the f_2' seen by Gray et al.[17] *in the channel $\bar{p}n \rightarrow \pi^- f_2' \rightarrow \pi^-\pi^+\pi^-$ are one and the same state.* The f_2' appears as a peak in the $\pi^+\pi^-$ mass and also in $\bar{p}p \rightarrow \pi^0 f_2'$, $f_2' \rightarrow 2\pi^0$, with comparable mass and width to the $X^0(1480)$. The decay $f_2' \rightarrow K^+K^-$ was not seen, consistent with the observed suppression[18] of the $K^+K^-/\pi^+\pi^-$ ratio in $\bar{p}p$ annihilation from $L=1$ states. If f_2' were a glueball, on the other hand, one would expect to see a prominent K^+K^- mode. The claimed branching ratio[17] $B(\bar{p}n \rightarrow \pi^- f_2')B(f_2' \rightarrow \pi\pi) \approx 0.4\%$ is considerably smaller than than for $X^0(1480)$ via the $\rho\rho$ decay mode, suggesting that

$$\Gamma(X^0(1480) \rightarrow \rho\rho) > \Gamma(X^0(1480) \rightarrow \pi\pi). \quad (6)$$

The preference for the $\rho\rho$ decay mode can be qualitatively understood in a microscopic quark model[19] for QTB decays of the $N\bar{N}$ system at rest, where a suppression of decays of the type $N\bar{N}(L=1) \rightarrow ss(l_f=2)$ is found, of which $N\bar{N}(^{13}P_2) \rightarrow \pi\pi(l_f=2)$ is a special case. A suppression of this transition was also found by Kohno and Weise[20] in a different model.

In summary, we suggest that the $X^0(1480)$ peak seen by Bridges *et al.*[10] may be the first example of the long sought-after $N\bar{N}$ quasi-nuclear states. The production branching ratio, mass, width, quantum-number assignment $[2^{++}(0^+)]$, and dominant decay mode $[\rho\rho$ over $\pi\pi$ or $K\bar{K}]$ is consistent with theoretical predictions if $X^0(1480)$ is a $^{13}P_2$-$^{13}F_2$ $N\bar{N}$ bound state. This object bears a special relationship to the $N\bar{N}$ entrance channel, since its production in the reaction $(N\bar{N})_{\text{atom}} \rightarrow \pi + (N\bar{N})_{\text{QN}}$ is optimal. It will not be easily seen in other channels, for instance $\pi + N \rightarrow X^0(1480) + N$, since here the production of ordinary $Q\bar{Q}$ mesons prevails. A structure near the $\rho\rho$ threshold has also been seen[21] in $\gamma\gamma \rightarrow \rho^0\rho^0$. The partial-wave analysis of Althoff *et al.*[21] suggests mostly 0^{++} strength below 1700 MeV/c^2 and 2^{++} at higher mass. This structure, which has been interpreted[22] in terms of interfering $I=0,2$ $Q^2\bar{Q}^2$ resonances, may be related to the $X^0(1480)$.

The $2^{++}(0^+)$ $N\bar{N}$ state should be accompanied by broad $1^{--}(0^-)$ and $0^{++}(0^+)$ structures at lower mass, the latter being the ground state of the $I=0$, natural-parity $N\bar{N}$ quasinuclear band. In contrast to $^{13}P_2$-$^{13}F_2$, the $^{13}P_0$ state would prefer to decay[19] into $\pi\pi(l_f=0)$ rather than $\rho\rho$. This mass region is complicated, since other $0^{++}(0^+)$ structures have been observed.[23]

Near the $N\bar{N}$ threshold, one anticipates the existence of further broad $N\bar{N}$ or $Q^2\bar{Q}^2$ objects. If these lie in the continuum, they are best looked for in particular exclusive two-body channels rather than in total cross sections. Just below threshold, the reaction $\bar{p}p \rightarrow \gamma X^0$ is an appropriate tool in the search for broad structures X, but only if the charged decay products of X^0 are studied in coincidence with the γ. The inclusive γ spectrum is useful in the search for narrow states, but not for new broad ones. The study of the reaction $\bar{n}p \rightarrow \pi^+ X^0(1480) \rightarrow 3\pi^+2\pi^-$ at very low momentum is recommended, since one thus evades the question of meson-nucleon final-state interactions which arises for $\bar{p}d \rightarrow p_s\pi^- X^0$.

The $N\bar{N}$ system offers a unique window for the study of new mesons with quark-antiquark structure more complicated than $Q\bar{Q}$. The study of annihilation processes, from initial states of different L, should be vigorously pursued.

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are given for the f_2', whereas in Ref. 10 the values are $M = 1522 \pm 7$ MeV and $\Gamma = 59 \pm 12$ MeV. This would appear to preclude the identification of f_2' and $X^0(1480)$ as the same state. However, these values of $\{M, \Gamma\}$ are sensitive to the assumed background in the f_2' region due to the $\pi^- f$ channel. An effective width of 262 MeV rather than the observed width of 180 MeV was used for the f in Ref. 10, leading to an upward shift of the f_2' mass relative to the observed peak at 1480 MeV in the $\pi^+\pi^-$ mass spectrum.

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