Narrow levels in the spectrum of quasinuclear $B\bar{B}$ bound states and resonances

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(Submitted October 10, 1975)
Zh. Eksp. Teor. Fiz. **70**, 805–810 (March 1976)

The annihilation widths of quasinuclear $N\bar{N}$ mesons were calculated. It is shown that in states with nonvanishing angular momentum small decay widths (10 MeV or less) for decays into pion channels are theoretically likely. The elastic widths of $N\bar{N}$ resonances near thresholds have been calculated. The possible existence of other narrow quasinuclear $B\bar{B}$ resonances (where B is a hyperon or nucleon) is discussed in light of the latest data.

PACS numbers: 14.40.–n, 13.25.–k

The experiments of the past few years indicate the existence of heavy mesons that are strongly coupled to the nucleon-antinucleon channel. In our previous papers (cf. [1] and references therein) we have predicted the possibility of the existence of such objects, conditioned, firstly, by the interaction of the nonrelativistic N and $\bar{N}$ on account of t-channel exchange of light mesons (π, η, ρ, ω) and, secondly, by the relatively small radius of the annihilation region. The latter leads to the circumstance that a bound or resonant $(N, \bar{N})$ system is in many respects similar to a nucleus, in spite of the annihilation. The spectrum of states of such a "quasinucleus" (with baryon number zero) turns out to be quite rich (owing to the strongly attractive spin-orbit interaction the total number of levels is around twenty). This means the presence of large number of mesons in the mass region close to two nucleon masses.

In the present paper we show that such "quasinuclear mesons" may have unusually narrow widths for decays into pionic channels (Secs. 1 and 2). Based on estimates for various $(N\bar{N})$ states, we have already called attention to this effect (cf. [1]). Here we report for the first time results which give a qualitative idea of the whole picture. This is important, in particular, for the explanation of the recently discovered discrete spectrum of gamma rays which accompany the annihilation of stopped $\bar{p}$ in deuterium (cf. [2])[1].

1. The possible smallness of annihilation widths of the $(N\bar{N})$ mesons is due to the inequality $r_a \ll R$, where r_a is the annihilation radius and R is the radius of the bound (or resonant) quasinuclear $(N\bar{N})$ state. As the calculations carried out in the OBE model[1] show, $R = 1 - 1.5$ F for states with a nonrelativistic mass defect.

The radius of the annihilation region is subject to the inequality: $r_a \leqslant \frac{1}{2}m$ (m is the nucleon mass, $\hbar = c = 1$). This follows formally from the position of the nearest singularities of the annihilation diagrams with respect to the momentum transfer (cf. [6]). The physical content of the inequality for r_a reduces to an uncertainty relation. Since the disappearance of the fermions in annihilations into bosons must be strictly simultaneous, the annihilating particles must be located at the same space point. The annihilation of the N and $\bar{N}$ separated by a distance r_a occurs on account of the fact that at the site of one of the particles, say N, a virtual pair $N'\bar{N}'$ is created in the time interval $\Delta t \leqslant \frac{1}{2}m$. Then the antinucleon $\bar{N}'$ annihilates with N and the nucleon N' annihilates with the "original" $\bar{N}$, if they manage to meet within the time Δt. This is possible if r_a satisfies the inequality indicated above.

In the first approximation with respect to the small parameter r_a/R the annihilation widths Γ of the system $(N\bar{N})$ can be calculated according to the equation

$$\Gamma = v_i \sigma_i \overline{|\Psi(r_a)|^2}. \tag{1}$$

Here v_i is the relative velocity of the N and $\bar{N}$, σ_i is the "internal" annihilation cross section without allowance for the peripheral t-channel exchanges and the centrifugal barrier, and Ψ is the $N\bar{N}$ wave function (the bar denotes averaging over a region of radius r_a).

For a nonrelativistic $N\bar{N}$ system the behavior of the Ψ-function at distances of order $1/m$ should not have a marked influence on the binding energy (otherwise the potential approach would be impossible). This implies that $\overline{|\Psi(r_a)|^2}$ cannot exceed in order of magnitude the average density, i.e.,

$$\overline{|\Psi(r_a)|^2} \leqslant (3/4\pi) R^{-3}. \tag{2}$$

If we assume for σ_i the value 45 mb/v equal to the experimentally observed annihilation cross section for $p\bar{p}$ in the s wave, it follows from (1) and (2) that $\Gamma \lesssim 100$ MeV for $R \approx 1.4$ F. For states with nonvanishing angular momentum one can introduce into the right-hand side of (2) a factor that accounts for the centrifugal barrier and thus reduces the value of the Ψ function at small distances. This factor will be absent if the centrifugal barrier is compensated by a strong attraction at small distances. On the other hand, the repulsion at distances of the order r_a occurs even in s states, at least for three reasons: owing to relativistic corrections (quadratic in the potential), owing to t-channel exchange of heavy mesons (with mass of the order $2m$), and owing to tensor forces (in this case the sign of the effective potential in the radial equation for the s wave depends on the sign of the wave function in the d state.

It is therefore essential to understand the scale of the quantities Γ for a physically reasonable effective repulsion at small distances. A good understanding can be gained from a model with an uncompensated centrifugal barrier.

2. In the calculations carried out here we made use of the "static" variant of the OBEP (cf. [7]), in which the repulsive centrifugal potential $l(l+1)/mr^2$ was not cut off at small distances (as was done previously in [8] with the purpose of obtaining upper bounds on Γ). To estimate the annihilation widths of all the states, use was made of the value of σ_i given above. We note that the "internal" cross section σ_i is in fact not equal to the observed annihilation cross section in the s wave, since the latter includes the effect of the attractive OBE potential and the resonance effects produced by it. Therefore, substituting into Eq. (1) for σ_i the observed cross section we obtain an exaggerated estimate for Γ. The values of Γ turn out nevertheless to be relatively small and this indicates that the narrowness of the nucleus-like $(N\bar{N})$ states is theoretically quite likely.

The wave functions and the level spectrum of the $(N\bar{N})$ system must be calculated starting from the Schrödinger equation with the OBE potential by means of the method of complex angular momenta. [9] This method is particularly convenient for numerical calculations in the case of resonant states ($M > 2m$, where M is the mass of the $(N\bar{N})$ system), since it allows one to formulate the boundary conditions without exponential growth of the wave function as $r \to \infty$. Together with the bound states the resonances lie on Regge trajectories $J(M)$ expressing the dependence of the angular momentum J of the system on the mass M (to physical values correspond integer values of $\mathrm{Re}\,J$). For a nonrelativistic $(N\bar{N})$ system there exist eight Regge trajectories corresponding to different values of the total spin $S = 0$ and 1, isospin $I = 0$ and 1 and the quantum number $S' = J - l = 0$ and ± 1. We note that in the nonrelativistic approximation states with different parities ($P = (-1)^{l+1}$) are on the same trajectory (when the s-channel annihilation exchanges are taken into account the nonrelativistic trajectory splits into two). One of the calculated trajectories ($S = 1$, $I = 0$, $S' = 1$) is shown in Fig. 1. On it there are two bound states and one resonance. In the case of the resonance we have $\mathrm{Im}\,J \neq 0$ and the curve for $\mathrm{Im}\,J$ determines the elastic width:

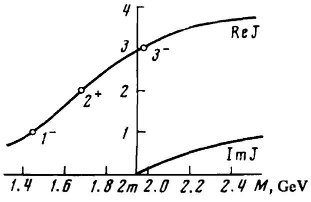

FIG. 1. The Regge trajectories for the quasinuclear mesons ($S = 1$, $I = 0$, $S' = J - l = 1$).

The spectrum of bound and resonant states of the $N\bar{N}$ system

$^{2S+1}L_J$	$I^G(J^P)$	M, MeV	Γ_a, MeV	$\Gamma_{N\bar{N}}$, MeV
$^1s_0$	$1^-(0^-)$ $0^+(0^-)$	1714 1678	151 149	
$^3s_1-{}^3d_1$*	$1^+(1^-)$ $0^-(1^-)$	1710; 1970 1395; 1515	163; 1.3 88; 1.1	–; 57
$^1p_1$	$1^+(1^+)$ $0^-(1^+)$	1858 1824	7.4 8.3	
$^3p_0$	$1^-(0^+)$ $0^+(0^+)$	1768 1330	13.3 8.2	
$^3p_1$	$1^-(1^+)$ $0^+(1^+)$	1825 1438	9.2 11.5	
$^3p_2-{}^3f_2$*	$1^-(2^+)$ $0^+(2^+)$	1878; – 1684; 1860	6.8; – 9.8; 0.1	
$^3d_2$	$1^+(2^-)$ $0^-(2^-)$	2030 1775	1.2 0.9	157
$^3d_3$	$1^+(3^-)$ $0^-(3^-)$	– 1978	– 1	– 78
$^3f_3$	$1^-(3^+)$ $0^+(3^+)$	– 2085	– 0.12	– 73
$^3g_3$	$1^+(3^-)$ $0^-(3^-)$	– 2230	– 0.01	– 76

Note. The asterisks denote orbital states which are mixed by the tensor interaction.

$$\Gamma_{N\bar{N}} = 2\,\mathrm{Im}\,J \Big/ \frac{d(\mathrm{Re}\,J)}{dM}. \qquad (3)$$

The order of magnitude of the width is $\Gamma_{N\bar{N}} \simeq 1/mr^2$. For $R = (1 - 1.5)$ F this yields $\Gamma_{N\bar{N}} = 50-20$ MeV. It should be noted that Eq. (3) is valid only for sufficiently small $\mathrm{Im}\,J$, i.e., near the threshold for the decay into $N\bar{N}$. As $\mathrm{Im}\,J$ increases the quantity $\Gamma_{N\bar{N}}$ begins to depend strongly on the properties of the potential in the complex plane of the radial variable r. The analyticity-destroying cutoff of the OBE potential (which is inevitable on account of the presence of the singularities of the type r^{-3}), particularly if carried out at not too small distances (in the version used by us of the static OBE variant this happens for $r \leq 0.6$ F), may strongly influence the magnitude of $\Gamma_{N\bar{N}}$. For this reason the values of $\Gamma_{N\bar{N}}$ obtained here should only be considered as estimates.

The fact that the elastic widths calculated according to Eq. (3) (cf. the table) are in qualitative agreement with the estimate based on physical considerations indicates in particular that in its general trait the model is correct and therefore can be used for heuristic purposes.

Figure 2 shows examples of wave functions of bound and resonant states. It can be seen from the figure that the annihilation region (indicated by shading) con-

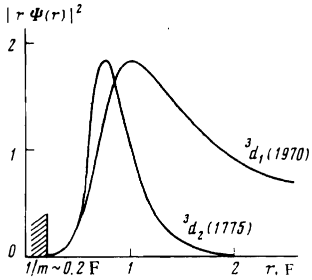

FIG. 2. The wave functions of the bound state ($M < 2m$) and of the resonant state ($M > 2m$) of the $N\bar{N}$ system.

tains a small fraction of the normalization integral. This is responsible for the smallness of the annihilation widths. The figure also shows that the resonance states are just as well localized as the bound states: a difference in energies of the order of hundreds of MeV does not substantially alter the wave function, affecting only its asymptotic behavior as $r \to \infty$. This gives us reason to consider that the presence of near-threshold resonances in the $(N\bar{N})$ system is theoretically less likely than the existence of bound states.

The fundamental result is concentrated in the fourth column of the table. From these data it can be seen that the annihilation widths drop sharply when one goes from s states to states with $l \neq 0$. As l increases by one unit the quantity Γ decreases by one order of magnitude, reaching 10 keV for $l = 4$. It is essential that for given l the values of Γ depend weakly on the other quantum numbers. The latter is partially due to the adopted value of σ_i, which is the same for all states, but at the same time it indicates that the repulsion at small distance (here of a centrifugal origin) necessarily and strongly suppresses the annihilation widths, independently of the details of the behavior of the wave function of the chosen state of the $(N\bar{N})$ system. In this sense the conclusion that they are "narrow" seems to us to be quite well founded.

In addition to the annihilation widths Γ the table contains the values of the masses of the $(N\bar{N})$ states resulting from our calculations. In this connection we would like to stress the fact that with the present accuracy of the phase shifts of NN and $N\bar{N}$ scattering it is impossible to count on the selection of a potential which would guarantee a reliable prediction of the masses of the $(N\bar{N})$ states for any choice of quantum numbers (it suffices to remember that today tens of different potentials are known which describe nonrelativistic NN scattering more or less satisfactorily). Thus the masses listed in the table can hardly be considered as data which are subject to direct comparison with experiment as a test of the model under consideration. It is more justifiable to pose the problem in reverse: reconstruct the Hamiltonian of the nuclear interaction of nonrelativistic nucleons from the observed spectrum of $(N\bar{N})$ levels.

If the proposed physical picture will turn out as a whole to be in agreement with the facts, then nuclear physics will receive, in addition to the one-level deutron which it had until now, a new "hydrogen atom": a (mainly) two-particle nuclear system with a rich spectrum of states.

A comparison of the masses of the $(N\bar{N})$ states obtained here with those calculated earlier in the model with compensated centrifugal repulsion at small distances (cf.[8]) shows that although there is a noticeable level shift from magnitudes of 50 MeV ($l = 1$) to 400 MeV ($l = 4$), the total number of levels remains the same. In other words, repulsion at distances essential for annihilation decreases substantially (from one to four orders of magnitude) the widths, yet leaves the other features of the model qualitatively unchanged.

One can therefore assert, based on current concepts on the interaction of nonrelativistic particles, that one should expect a large number (of the order of ten) or relatively narrow near-threshold states of the $(N\bar{N})$ system.

3. We would like to make some remarks on the possible existence of other nucleus-like baryon-antibaryon systems, e.g., of the type $Y\bar{N}$ or $Y\bar{Y}$ ($\bar{Y}$ denotes a hyperon). In recent years this question has been discussed in a number of papers (cf.[10,11]), in particular in relation to the discovery of the new bosons ψ and ψ'.[12,13] Theoretically bound $Y\bar{N}$ states have been considered before.[14] Since data on the $Y\bar{N}$ and $Y\bar{Y}$ interactions are rather sparse, detailed calculations of the levels of such systems (even in a heuristic sense) are hardly justified at the present. Nevertheless it is clear that the exchange of an ω meson which is possible between any baryons must lead to a strong baryon-antibaryon channel attraction even at distances of the order of 1 F. It is for this reason that the existence of nucleus-like systems of the type mentioned above seems to us to be quite likely.

However, we do not think that the ψ particles can be interpreted as a bound state and a resonance in the $\Omega\bar{\Omega}$ system. In the framework of such a model it is difficult to understand first, the too large relative probability for the decay of the ψ into leptonic channels and second, the absence of the decay mode $\psi' \to \Omega\bar{\Omega}$ (the partial width for this channel decay should be at least of the order of 1 MeV, i.e., at any rate the main part of the total width of the ψ').

In conclusion we stress that the possible existence of nucleus-like systems of real baryons and antibaryons (and not of hypothetical quarks) is based on the smallness of the sizes of the annihilation region in comparison to the radius of the bound state. It is the "looseness" of the system in the sense indicated above that leads to the smallness of the annihilation width. This means, on the other hand, that the annihilation interaction must not introduce a substantial contribution to the formation of the state itself, which is essentially created by the exchange of light bosons, in the same manner as that responsible for the nuclear forces between the NN. This signifies that the multichannel nature of the $N\bar{N}$ annihilation and the implied many-sheetedness of the Riemann surface in the complex energy variable have in the present model secondary importance: the $(N\bar{N})$ systems under consideration are essentially two-particle systems. This somewhat distinguishes our approach to the problem of nucleus-like $(N\bar{N})$ states from the views expressed recently in the papers of Chew and Koplik.[15,16]

The authors express their gratitude to B. O. Kerbikov for numerous useful discussions.

1)A theoretical interpretation of the results of the paper of Kalogeropoulos *et al.*[2] can be found in our preprint.[3] In a recent paper of the same authors,[4] the discrete gamma lines were not observed (the upper limit on the intensity of a separate line is less than 3.3% for a natural width much smaller than 10 MeV). This experiment, which is distinguished by a high statistical accuracy is nevertheless hard to interpret owing to the low energy resolution. On the other hand, the new data given in the review by Kalogeropoulos[5] repeat the results of[2] (with higher statistical significance). We note that narrow $(N\bar{N})$ states (with a width of the order of several MeV) have been observed by a series of authors directly in hadronic channels (cf. the references in[3] and[5]).

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Translated by M. E. Mayer