Quasinuclear levels of the $\Lambda\bar{\Lambda}$–$\Sigma\bar{\Sigma}$ system

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The amplitudes for elastic scattering and for transitions $\Sigma\bar{\Sigma}\to\Lambda\bar{\Lambda}$ are calculated for orbital angular momenta $L = 1, 2$. Coupling with a closed channel substantially reduces the widths of the resonances but has only a negligible effect on the positions of the resonances. Recommendations are offered for an experimental search and a possible interpretation of the most recent data.

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The startup of a slow-antiproton storage ring, expected in the near future,[1] has added to the need for solutions of certain problems in the theory of quasinuclear baryonium which has not been studied adequately. One of these questions is how the coupling of the various baryon (B)–antibaryon ($\bar{B}$) channels affects the spectrum of quasinuclear resonances. The exchange of the same bosons leads to both a potential diagonal interaction and a transition between different $B\bar{B}$ channels. Previous research has been devoted primarily to the interaction within some channel.[2] Only in Ref. 3 do we find a study of the $N\bar{N}$ resonance which arises from the $\Sigma\bar{\Sigma}$ bound state due to $\Sigma\bar{\Sigma}\to N\bar{N}$ transitions.

In this letter we report a study carried out to determine the properties of the quasinuclear system $\Lambda\bar{\Lambda}$–$\Sigma\bar{\Sigma}$ with allowance for possible transitions between these pairs. We focus on to questions: How does the coupling of channels affect the widths of the resonances? What manifestations of these resonances can we expect in the experimental cross sections? Although the parametrization of the Hamiltonian used for the numerical calculations is realistic, i.e., does correspond to the most recent information on the one-boson exchange constants, we have in mind here primarily the qualitative behavior. The qualitative behavior is not a trivial question and, as we will see below, is important for an experimental search.

The nonrelativistic approximation, which leads to the one-boson-exchange potentials,[4] is valid for resonances near the threshold. In this approximation the spin-orbit direction is singular at short range. It is regularized by introducing the cutoff

$$V_{ij}(r < r_c) = 0.$$

Here $i, j = 1, 2$ (1, 2 are the $\Lambda\bar{\Lambda}$ and $\Sigma\bar{\Sigma}$ channels); V_{ij} are the elements of the (2×2) interaction Hamiltonian; r is the distance between the particles; and $r_c = 0.64$ fm is the cutoff radius.[2)] To simplify the calculations we ignore tensor forces. Study of the $N\bar{N}$ systems has shown that tensor forces are not really important for extracting the qualitative behavior. In contrast, the spin-orbit interaction, which partially cancels the centrifugal repulsion, plays a governing role, in fact giving rise to the levels of quasinuclear baryonium with nonzero orbital angular momenta.[2]

To calculate the three independent elements of the two-channel reaction matrix, we use the method of phase functions.[5] In this case this method leads to a system of three nonlinear first-order differential equations, which has been solved numerically (by the method described in Ref. 6).

The calculations yield the elastic-scattering amplitudes in both channels and the amplitudes for the transitions $\Sigma\bar{\Sigma}\to\Lambda\bar{\Lambda}$ for the orbital angular momenta $L = 1, 2$ over the range from 0 to 500 MeV for the total kinetic energy of the Λ and $\bar{\Lambda}$ (in the c.m. frame of the pair). The resonance levels and widths are determined from Argand diagrams (from the velocity of the points in the plane of the complex amplitude upon a change in the energy). Figure 1 shows a representative Argand diagram for the amplitudes for the elastic scattering of $\Lambda\bar{\Lambda}$ and $\Sigma\bar{\Sigma}$ in the $^3P_1$ state. This diagram corresponds to a resonance with a total energy (mass) of 2394 MeV and a width $\Gamma = 27$ MeV. All the resonance in the P and D waves found in this manner are listed in Table I. Also shown here is the role played by the channel coupling. We see from this table that the widths of the resonance between the thresholds for $\Lambda\bar{\Lambda}$ (2231 MeV) and $\Sigma\bar{\Sigma}$

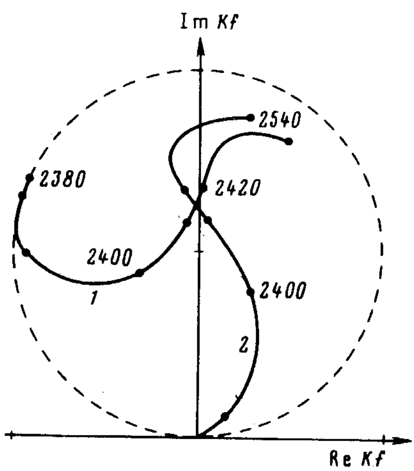

FIG. 1. Argand diagram for $k_1 f_{11}$ (curve 1) and $k_2 f_{22}$ (curve 2). Here k_1 and k_2 are the relative momenta of the Λ and $\bar{\Lambda}$ and the Σ and $\bar{\Sigma}$; f_{11} and f_{22} are the amplitudes corresponding to $^3P_1$. The labels on the points are the total energies in MeV.

(2386 MeV) decrease significantly because of the channel coupling. A particularly instructive example here is the $^3D_1$ resonance, whose width decreases by nearly an order of magnitude (from 105 to 15 MeV). The physical reason for the effect involves an additional attraction between the light particles ($\Lambda\bar{\Lambda}$) which results from the coupling with a closed ($\Sigma\bar{\Sigma}$) channel. This attraction can be seen clearly in the decrease in the excitation energy (from 95 to 50 MeV in the case of the $^3D_1$ resonance). The lowering of a level due to the additional attraction leads to an exponential decrease in the transmission of the centrifugal barrier, i.e., to a pronounced decreased in the width of the resonance. The coupling of channels gives rise to yet another mechanism (mentioned in Ref. 3), which generates narrow resonances: The near-threshold heavy-particle state ($\Sigma\bar{\Sigma}$) will be seen as an anomalously narrow resonance above the barrier in the channel of the light particles ($\Lambda\bar{\Lambda}$). In this case we are thus dealing with the resonance $^3P_2$ (2399), with a width $\Gamma = 23$ MeV, which corresponds to a kinetic energy $E(\Lambda\bar{\Lambda}) = 168$ MeV at a centrifugal-barrier height $V_c \approx 15$ MeV. There is an analogous situation for the $^1P_1$ (2403), $^3P_0$ (2396), and $^3P_1$ (2394) resonances (Table I). For the resonance above the barrier we would naturally expect $\Gamma \gtrsim 100$ MeV [as, for example, for the resonance $^3D_2$ (2331), for which we have $E(\Lambda\bar{\Lambda}) \approx 100$ MeV, $V_c \approx 85$ MeV, and $\Gamma = 110$ MeV]. The comparatively small widths of these P resonances in the $\Lambda\bar{\Lambda}$ system is a consequence of the narrow near-threshold resonance level in the $\Sigma\bar{\Sigma}$ channel, generated by the diagonal one-boson exchange.

Figure 2 shows the energy dependence of the cross sections near the $^3P_1$(2394) resonance. Remarkably, the irregularity in the $\Lambda\bar{\Lambda}$ elastic scattering (reason is an

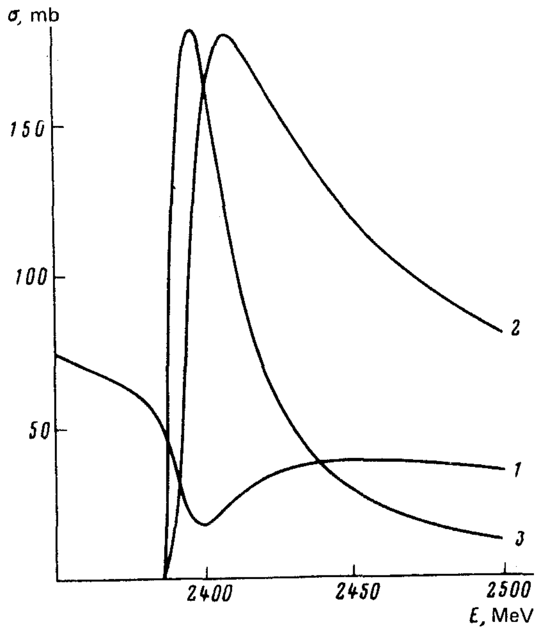

FIG. 2. Dependence of the $^3P_1$ cross sections of the elastic scattering $\Lambda\bar{\Lambda}$ (curve 1), the elastic scattering $\Sigma\bar{\Sigma}$ (curve 2), and the reaction $\Sigma\bar{\Sigma}\rightarrow\Lambda\bar{\Lambda}$ (curve 3) on the total energy near the $^3P_1$ (2394) resonance.

TABLE I. Spectrum of isoscalar P and D levels of the quasinuclear system $\Lambda\bar{\Lambda}$–$\Sigma\bar{\Sigma}$ with $(\Lambda\bar{\Lambda}+\Sigma\bar{\Sigma})$ and without $(\Lambda\bar{\Lambda},\ \Sigma\bar{\Sigma})$ coupling of channels ($2m_\Lambda = 2231$ MeV; $2m_\Sigma = 2386$ MeV).

$^{2S+1}L_J$	Mass (MeV)			$\Gamma = \Gamma_{\Lambda\bar{\Lambda}} + \Gamma_{\Sigma\bar{\Sigma}}$ (MeV)			$\Gamma_{\Lambda\bar{\Lambda}}/\Gamma$
	$\Lambda\bar{\Lambda}+\Sigma\bar{\Sigma}$	$\Lambda\bar{\Lambda}$	$\Sigma\bar{\Sigma}$	$\Lambda\bar{\Lambda}+\Sigma\bar{\Sigma}$	$\Lambda\bar{\Lambda}$	$\Sigma\bar{\Sigma}$	$\Lambda\bar{\Lambda}+\Sigma\bar{\Sigma}$
$^3P_0$	$\lesssim$ 2211	2211	–	–	–	–	–
	2396	–	2391	34	–	6	0.46
$^3P_1$	$\lesssim$ 2226	2226	–	–	–	–	–
	2394	–	2392	28	–	6	0.46
$^3P_2$	2241	2241	–	12	15	–	1
	2399	–	2398	23	–	19	0.2
$^1P_1$	2247	2251	–	29	48	–	1
	2403	–	2402	50	–	27	0, 42
$^3D_1$	2280	2328	–	15	105	–	1
$^3D_2$	2330	2340	–	110	200	–	1

interference with "its own" bound state in the $\Lambda\Lambda$ channel generated by the diagonal one-boson exchange, which lies extremely near the threshold (the binding energy is $E_B \approx 5$–10 MeV). The resonance peaks are clearly visible in the cross sections for the $\Sigma\bar{\Sigma}$ elastic scattering (curve 2) and the reaction $\Sigma\bar{\Sigma}\to\Lambda\bar{\Lambda}$ (curve 3). The very different behavior of the excitation curves near the same resonance in the different channels is a fact of importance for experimental searches.[3)] Previous attempts have been made to observe the near-threshold $\Lambda\bar{\Lambda}$–$\Sigma\bar{\Sigma}$ resonances in production reactions. There is now some evidence that resonances of this type are present in the $\Lambda\bar{\Lambda}$ channel.[9] We might also note that the 2^+ isoscalar resonances with masses of 2160 and 2320 MeV which were recently discovered in the system of two φ mesons[10] may prove to be quasinuclear $\Lambda\bar{\Lambda}$–$\Sigma\bar{\Sigma}$ states (in this case the 2320 resonance should, very probably, decay by the $\Lambda\bar{\Lambda}$ channel).[4)]

It can be seen from these results that reliable detection of near-threshold hyperon–antihyperon resonances of quasinuclear origin may require an energy resolution on the order of 1 MeV, a mandatory distinction of certain partial waves, and a good statistical base. Such conditions can be arranged on the LEAR device in experiments on $p\bar{p}\to\Lambda\bar{\Lambda}$ or $p\bar{p}\to\Sigma\bar{\Sigma}$. The properties of the system of three coupled channels, $p\bar{p}$–$\Lambda\bar{\Lambda}$–$\Sigma\bar{\Sigma}$, near the $\Lambda\bar{\Lambda}$ and $\Sigma\bar{\Sigma}$ thresholds should be qualitatively similar to those discussed above. Detailed calculations will be published separately.

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[2)]We also tried some other cutoff versions. As expected, the particular nature of the regularization of the Hamiltonian at short range does not affect the basic properties of the quasinuclear states.

[3)]We wish to emphasize that this circumstance has been pointed out previously[7] in connection with the manifestation of the $N\bar{N}$ (1940) resonance in the $p\bar{p}$ elastic scattering and the absence of the corresponding peak from the energy dependence of the cross section for the charge exchange $p\bar{p}\to n\bar{n}$. It was concluded in Ref. 7 on this basis that the so-called h^0 (2040) meson may be of a quasinuclear nature and that there may be a branching ratio of about 0.5 for decay through the $p\bar{p}$ channel. This type of decay of the h^0 meson was apparently observed recently.[8] The relatively larger branching ratio of the h^0 meson in the K^+K^- channel can be attributed in the quasinuclear approach to a coupling with $\Lambda\bar{\Lambda}$ and $\Sigma\bar{\Sigma}$ channels.[3]

[4)]As was pointed out by O. D. Dal'karov, these resonances were tentatively identified in Ref. 10 as gluonium, since their production in the reaction $\pi^-p\to n2\varphi$ is forbidden by the quark selection rules.

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