Strange exotic meson resonances of the quasinuclear type in the mass range near 2 GeV

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It is shown that the mass region near 2 GeV should contain strange exotic mesons in the form of quasinuclear bound and resonance states of the system $\Sigma\bar{N}$ with isospin $I=3/2$. The theoretically possible widths of these mesons range between 10^{-2} and 10^2 MeV.

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The existence of nuclear bound and resonance states in the nucleon-antinucleon system ($N\bar{N}$) was predicted theoretically[1] and was observed experimentally in a number of experiments with slow antiprotons.[2]

The spectrum of bound and resonance states of the $N\bar{N}$ system was calculated by a number of authors[1,3] using the one-boson exchange potentials (OBEP) describing data on low-energy $N\bar{N}$ scattering. The structure of OBEP (which isolates exchanges of mesons with known G parity) is such that it can be used to describe both NN and $N\bar{N}$ scattering.

The essential point for the entire theory is that $N\bar{N}$ annihilations occur at distances smaller than or of the order of half the Compton wavelength of the nucleon, whereas the radius of the quasi-nuclear states is of the order of the Compton wavelength of the pion. It may, therefore, be assumed in the first approximation that annihilation effects do not modify the overall shape of the spectrum obtained by solving the Schrödinger single-channel potential problem with a real potential. On the other hand, the availability of a small parameter (the ratio of the annihilation radius to the radius of the orbit) enables us to estimate the annihilation level width from the wave function of the quasinuclear state in the annihilation region and the annihilation cross section at low relative velocities (further details of this are given elsewhere[1,4]). Since the amplitude of the wave function at small distances is small for states with nonzero orbital angular momenta, the annihilation widths of such levels are small (of the order of 1, 10, and 100 MeV for d, p, and s levels, respectively). Moreover, the decay widths for the $N\bar{N}$ channel (for resonances) are relatively large (of the order of the annihilation widths). It follows that the theoretical scheme predicts an abundance of narrow boson resonances with mass near 2 GeV and strongly connected with the $N\bar{N}$ channel.

Despite the abundance of data on nucleon-nucleon scattering, there are many different variants providing good descriptions of NN scattering even within the framework of one class of potential (namely, OBEP). However, the common feature of all the OBEP variants is the strong repulsion at small distances ($r \lesssim 0.5$ F) due to the exchange of the G-odd ω meson.

On the other hand, in the problem of bound and resonance states of the $N\bar{N}$ system, the overall appearance of the spectrum is determined by attraction due to this exchange and, despite differences in the details of the situation (such as the relative position of the levels and even the number of levels), the phenomenon as a whole, i.e., the existence of a network of levels, is reproduced by all the one-boson exchange potentials.

Since ω exchange is possible between any baryons (B), it follows that, as noted by Bogdanov *et al.*,[4] a set of near-threshold bound and resonance states of the $B\bar{B}$ system should exist and the properties of these states (such as widths, etc.) should be similar to the properties of the quasinuclear $N\bar{N}$ systems. A recent calculation of the masses and level widths performed by Dover and Goldhaber[5] for the $Y\bar{Y}$ systems (where $Y=\Lambda, \Sigma, \Xi$) provides a good illustration of this proposition. Even before this work, Dal'karov and Mandel'tsveĭg[6] demonstrated the possibility of the existence of a spectrum of states of the $\Lambda\bar{N}$ system (the calculations were based on the Deloff potential,[7] which describes data on ΛN scattering and the binding energies of light hypernuclei).

In this paper, we consider the question of strange meson quasinuclear resonances with isospin $I=\frac{3}{2}$, i.e., the so-called exotic mesons. If the $\bar{\Sigma}^{+}p$ or $\Sigma^{-}\bar{p}$ systems have bound or resonance states, the double-charged strange mesons might be observable in the mass range near 2 GeV. It was shown in[8] that the 1976 ±15 MeV resonance in the system $K^{\pm}\pi^{\mp}\pi^{\mp}$, which has a width $\Gamma < 40$ MeV,[9] may turn out to be a nuclear-like bound state of the nucleon-antihyperon system (this hypothesis is at least not inconsistent with experimental data).

More extensive studies, as compared with the work of Dal'karov and Mandel'tsveĭg,[6] of systems such as $Y\bar{N}$ can be begun by using the potential given by Nagels, Rijken, and Swart,[10] which describes NN, ΛN, and ΣN scattering. This potential contains exchanges of nonets of pseudoscalar (π, η, K, X^0) and vector ($\rho, \varphi, K^*, \omega$) mesons, and the scalar meson ε which is an $SU(3)$ singlet. The coupling constants between the nonstrange mesons and the nucleons are determined by numerical fits to NN data. The hyperon-nucleon data can, at least in principle, be used to remove indeterminacies in those constants that cannot be unambiguously determined on the basis of nucleon-nucleon data alone. The meson-baryon coupling constants in this potential are subject to $SU(3)$ symmetry relations

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TABLE I

Mesons	Mass, MeV	g_{NN}	f_{NN}	$g_{\Sigma\Sigma}$	$f_{\Sigma\Sigma}$
π	138	3,66	–	3,55	–
η	549	2,73	–	2,92	–
X^0	957	3,89	–	3,85	–
ρ	770	0,59	4,82	1,19	3,22
φ	1019	−1,12	−0,51	−1,96	1,75
ω	784	3,37	2,34	2,78	3,94
ε	760	5,03	–	5,03	–

(symmetry violation is represented only by the fact that physical values of the masses are taken for the baryons and the mesons; a more detailed account of the procedure used to determine the parameters of the potential is given in original papers[10]).

In our calculations, we used the OBEP potential with the baryon-meson coupling constants taken from the paper by Nagels *et al.*[10] (Table I). The infinite repulsion at short distances in the BB and $B\bar{B}$ systems was replaced by a "cutoff" in the potential at distances less than some particular value r_0[1)] (the potential was assumed to be zero at short distances, as in our previous calculations on the $N\bar{N}$ system[11]). We excluded infinite repulsion because it was difficult to interpret physically. On the other hand, the cutting off of the attractive potential in the $B\bar{B}$ system is equivalent to the presence at short distances of a repulsive potential additional to the OBEP and due to relativistic corrections and, possibly, boson exchanges that have not been taken into account. This type of simplification is admissible in heuristic calculations which do not pretent to provide an accurate comparison between theoretical predictions of level positions and experimental data. In the present state of the theory, we believe that the main problem for the theory of $B\bar{B}$ systems is to establish the very possibility of existence of such systems in different channels, to obtain an overall qualitative picture of the spectrum, and to predict the gross properties of the bound and resonance states of the $B\bar{B}$ system, so that such quasinuclear compound systems can be distinguished experimentally from other heavy bosons. Moreover, we believe that the converse problem can also be legitimately formulated, namely, how to use the observed spectrum of $B\bar{B}$ levels to obtain information on the Hamiltonian for the nuclear interaction between nonrelativistic baryons.

The level positions were determined by solving the nonrelativistic Schrödinger equation. For $r > r_0$, the potential contains the central, spin-spin, tensor, spin-orbital, and quadratic spin-orbital interactions. We took into account the diagonal matrix elements of the tensor forces, but tensor mixing ($^3s_1 - {^3d_1}$; $^3p_2 - {^3f_2}$) was ignored. We also ignored exchange interactions due to strange mesons (their coupling constants with the baryons are small[10].)

The spectrum of bound and resonance states of the $\Sigma\bar{N}(I = \frac{3}{2})$ system is shown in Fig. 1a. It contains five levels, two of which ($^{2S+1}L_J = {^1p_1}; {^3p_2}$) lie above the threshold ($m_N + m_\Sigma = 2136$ MeV). Of course, the position of the levels is very sensitive to the cutoff radius at short distances, and the most "vulnerable" levels

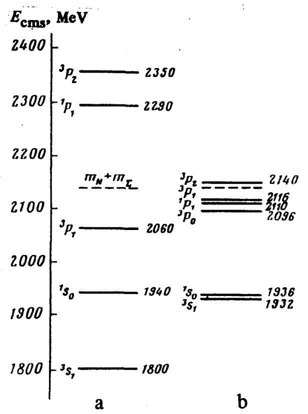

FIG. 1. Spectrum of the bound and resonance states of the system $\Sigma\bar{N}(I=3/2)$. The quantum numbers of the states $^{2S+1}L_J$ and the masses (in MeV) are indicated. a) Calculation with the Nagels, Rijken, and de Swart potential.[10] Zero potential is assumed for $r_0 < 0.4$ F. b) Calculation based on the Bryan–Phillips potential.[11] The transition to the description of the system $\Sigma\bar{N}$ is based on the assumption that the meson-baryon coupling constants are subject to the $SU(3)$ symmetry relation. The cutoff radius is taken to be $r_0 = 0.6$ F.

are the highly bound s levels. We have investigated the "survival" of the $^1S_0$ level as a function of the cutoff radius. Table II shows the variation in the binding energy ε of the $^1s_0$ state as a function of r_0. It is clear that variations in r_0 within very broad limits result in a shift of the $^1s_0$ state within a reasonable range.

Another verification of the stability of the problem to variations of the potential is provided by the calculation of the spectrum of bound and resonance states of the $\Sigma\bar{N}$ system with the Bryan-Phillips potential.[11] This variant of OBEP describes NN and $N\bar{N}$ scattering. It contains π, η, ρ, ω meson exchanges and exchanges of two scalar mesons, namely, σ_0 and σ_1, which effectively represent two-pion exchanges. The transition to the potential for the $\Sigma\bar{N}$ system can be carried out with the aid of $SU(3)$ symmetry relations for the meson-baryon coupling constants. The cutoff radius of the Bryan-Phillips potential for the $\Sigma\bar{N}$ system was taken to be the same as for the $N\bar{N}$ system, namely, $r_0 = 0.6$ F.

Our test calculation can therefore be used to establish the "kinematic" difference between the $\Sigma\bar{N}$ and $N\bar{N}$ spectra due to the different masses of the baryons and the small (for Σ hyperons) change in the coupling constant with the mesons.[2)]

Our results obtained with the potential based on the Bryan-Phillips potential are shown in Fig. 1b. Although the distribution of the levels differs from that in Fig. 1a, there are qualitative similarities: the position of the p levels and their number are roughly the same near the threshold. We note that the inclusion of diag-

TABLE II

r_0, F	ε, MeV	r_0, F	ε, MeV
0,6	−7,4	0,4	−196
0,5	−50	0,3	<−500

onal matrix elements of tensor and quadratic spin-orbital forces produces a very slight change in the position of the levels in both forms of the potential: the maximum shift for the $^3p_1$ state is 100 MeV.

Comparison with the spectrum of the $N\bar{N}$ system (it is reasonable to compare with the isovector states of $N\bar{N}$: the corresponding potential has the same isotopic structure as for $\Sigma\bar{N}$ with $I=\frac{3}{2}$) shows the absence of these states. Nevertheless, the kinematic effect due to the change in the mass of the baryon has not removed the phenomenon: the $\Sigma\bar{N}$ system has a number of s and p states.

We note in connection with the foregoing that calculations of levels and of the corresponding wave functions of localized states with a complex potential, in which the imaginary part is independent of energy and other quantum numbers, [12] cannot be regarded as correct. This model (it is occasionally suitable for phenomenologic descriptions of scattering in the physical region) leads to incorrect analytic relationships for the amplitudes in the complex plane of energy and, therefore, to physically inadmissible spacetime properties of the wave functions for states in the discrete spectrum. This also applies to the formulation of energy-independent boundary conditions which take absorption into account. [13] When the level shift due to inelastic interactions is important, a coupled-channels calculation is unavoidable. [13,14]

We must now consider the annihilation widths of bound and resonance states of $\Sigma\bar{N}$. We begin by noting that the solution of this problem encounters much greater theoretical uncertainties than the determination of the energy spectrum of the states. We have shown that the qualitative picture of the spectrum can be described in a relatively stable fashion by potentials representing the peripheral part of the interaction ($0.4<r<1.5$ F). The annihilation interaction is localized mainly at distances of the order the Compton length of the baryon and provides a minor distortion of the peripheral part of the wave function of the bound system. At the same time, it may have a very substantial effect on the form of the wave function at short distances. Moreover, relativistic effects and t-channel heavy-meson exchanges, including exchanges of quasinuclear states, may play an important role in the real potential at short distances. We therefore consider it reasonable to give only the upper limits for the widths of the quasinuclear states. In the width formula

$$\Gamma=(v\bar{\sigma}_a)\,\overline{|\Psi(0)|^2} \tag{1}$$

we therefore replace $\overline{|\Psi(0)|^2}$ for the s state by the level density averaged over the entire volume, $\rho=(^4/_3\pi R^3)^{-1}$, where R is the radius of the system, $\bar{\sigma}_a$ is the "internal" annihilation cross section in the absence of the potential interaction, v is the relative velocity of the particles, and $\overline{|\Psi(0)|^2}$ is the mean density of the particles in the annihilation region. There are no data on the $\Sigma\bar{N}$ annihilation cross section at low energies. If we suppose that this cross section is of the same order as for the system $N\bar{N}$ (although it is probably somewhat smaller than the nucleon-antinucleon cross section), and if we replace the cross section for the channel with fixed quantum number by the total annihilation cross section $(v\sigma_a)_0=45$ mb, [11] we obtain $\Gamma_s\approx 100$ MeV for $R\sim 1$ F. For states with nonzero orbital angular momenta, we can introduce a factor representing the centrifugal repulsion. This leads to widths of the order of 10 MeV for the p states. As noted elsewhere, [14] even the s states may be substantially reduced in width for very obvious physical reasons, including relativistic corrections that are quadratic in the potential. [15] From the theoretical point of view, the most likely widths are therefore those in the range between 10^{-2} and 10^2 MeV.

We assume that the width estimates with allowance for the phenomenologic functional dependence of the annihilation interaction on distance[15] would take us outside the limits of accuracy.

Summarizing, it may be said that the existence of strange exotic ($I=\frac{3}{2}$) meson resonances with masses of about 2 GeV is very likely. There may be about five such quasinuclear states of the $\Sigma\bar{N}$ system. The widths of some of them may turn out to be quite small for the heavy mesons, the theoretically possible widths range up to 100 keV. Moreover, it is expected that this mass range will contain a group of strange mesons of quasinuclear origin with nonexotic quantum numbers, namely, the bound and resonance states of the $\Lambda\bar{N}$[6] and $\Sigma\bar{N}(I=\frac{1}{2})$ systems. There is some experimental evidence for the existence of such objects. [16] The experimental detection and investigation of the properties of these particles would provide important information on the nature of the hyperon-nucleon interaction.

1) The cutoff radius for s and p waves was assumed to be the same and given by $r_0=0.4$ F.

2) Since $g_{\Sigma\Sigma\pi}$ and $g_{NN\pi}$ differ by roughly 15%, we assumed that these two constants were almost equal.

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Effect of reduced mass in Stark broadening of hydrogen lines

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A theory is developed which describes the deformation of the Stark contour of hydrogen lines near the center, brought about by the thermal motion of the perturbing ions. The method of calculation is based on systematic perturbation theory with respect to the parameter $\dot{\Psi}\tau<1$, where $\dot{\Psi}$ is the characteristic rotation frequency of the ion field, while τ is the atom lifetime on the Stark sublevel and depends on the impact electron broadening $w\sim\tau^{-1}$. The main regularities of the "reduced mass effect" are explained, viz., the experimentally observed dependence of the spectral variation of the contour $I(\Delta\lambda)$ near the center of the hydrogen line on the concentration of the plasma N and the reduced mass of the perturbing ions μ. The effect is of interest as a means of determining the ion temperature T_i and of investigating the ion microfield fluctuations in the plasma.

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1. In the problem of the Stark broadening of spectral lines of the hydrogen atom, the reason for the systematic divergence of the calculated and observed shapes near the center has long remained unclear. These divergences have quite definite regularities: 1) the observed dip at the center of the lines without unshifted components (H_β, H_δ) is always less than theoretical; 2) for lines with unshifted components (H_α, H_γ) the observed intensity at the center is less and the halfwidth of the line is greater than calculated. Recently,[6,7] the supposition was advanced that the foregoing deviations are connected with the thermal motion of the ions. Experimental proof of such a connection was obtained by Wiese and coworkers,[8,9] who discovered the so-called reduced mass effect: the deformation of the central part of the line shape depends not only on the concentration of the charged particles N but also on the reduced mass of the exciting ion + radiating atom pair.

The largest amount of experimental data has been obtained for the H_β line, while the line contour was determined in Refs. 8, 9 principally by the static multiple mechanism of broadening

$$h_i=N\left(\frac{eC}{v_i}\right)^3\gg 1,$$

where C is the Stark constant, e is the charge of the electron, and v_i is the thermal velocity of the ions.

The method of taking into account the effects of thermal motion in the many-particle case $h_i\gg 1$, based on the calculation of corrections to the static contours in terms of the parameter $h_i^{-1/2}$, was first developed within the framework of adiabatic theory by Kogan.[10] However, calculations[5] based on the adiabatic theory[10] led to corrections which did not agree with experiment not only in magnitude but even in sign. The negative result of the analysis of Ref. 5 is not surprising since, as was shown in Ref. 11, the principal role near the center of the line is played by effects connected with rotation of the electric field intensity vector of the ions $\mathbf{F}$, which were not taken into account in the adiabatic theory.[10] In the present work, thermal corrections to the contour for the case $h_i\gg 1$ are considered with account of the electron impact broadening and rotation of the ion field.

2. In calculation of the line shape $I_{ab}(\omega)$, taking into account both the electron impact broadening and also the dynamics of the ion field, the starting point is the following expression for the correction function $K_{ab}(\tau)$ (see Refs. 11 and 12):

$$K_{ab}(\tau)=\sum_{\alpha,\beta,\alpha',\beta'}\Big\{\langle\alpha|\hat{d}(0)|\beta\rangle\langle\beta'|\hat{d}(\tau)|\alpha'\rangle$$

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