POSSIBLE QUASINUCLEAR NATURE OF HEAVY MESON RESONANCES

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It is shown that the potential interaction between a nucleon and an antinucleon at nonrelativistic energies leads to the existence of a number of nuclear-like bound states which manifest themselves as heavy meson resonances (with masses close to double the nucleon mass).

In the present paper the possibility is investigated of the existence of nonrelativistic bound states in the $N\overline{N}$ system. Our starting point is the potential which correctly describes $N\overline{N}$ scattering at low energies (up to 150 MeV in CMS). For such a potential we have used the static variant of the Bryan and Phillips[1] potential (in future referred to as the BP potential). The real part of this potential is obtained by the G-transformation of the Bryan and Scott[2] potential which satisfactorily reproduces the experimental phase shifts in NN scattering. This is essential since the present data on the scattering, charge exchange and $N\overline{N}$ annihilation are not sufficiently complete (cf.,[3,4]).

Compared with the nuclear two body problem the problem of the bound states of a nucleon and an antinucleon is made complicated by annihilation. The width and the shift of the level due to it are difficult to calculate with the same accuracy as the binding energy due to the potential interaction. However, these quantities can be estimated on the basis of the following consideration. The linear dimension R of a system of bound nonrelativistic particles satisfies the inequality $R \gg 1/m$ (m is the mass of the particle, $\hbar = c = 1$), but annihilation must occur at distances of the order of $1/m$. As a result of this in the bound state the nucleon and the antinucleon spend the greater part of the time outside the domain of annihilation. Thus, there exists in the problem a small parameter $1/mR$ and this enables us to estimate the width of the level by means of the formula

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

where v is the relative velocity of the nucleon and the antinucleon, σ_a is the cross section for annihilation at sufficiently low values of v, $\overline{|\Psi(0)|^2}$ is the average value of the density of the particles in the domain of annihilation. For $v\sigma_a \approx 45$ mb, $\overline{|\Psi(0)|^2} \approx 1/\pi R^3$, $R \approx 1.5–2$. Formula (1) yields $\Gamma \approx 100$ MeV[1)]. Corrections to (1) due to the finite size of the domain of annihilation are of order $(1/mR)^2$[5].

In a similar manner one can estimate the shift of the level. We denote by f_a the scattering amplitude due to annihilation diagrams. We have in the approximation of zero annihilation radius

$$\Delta E - i\frac{\Gamma}{2} = \frac{4\pi}{m}\overline{|\Psi(0)|^2}f_a, \quad f_a = \frac{1}{A+\varkappa}, \tag{2}$$

where $1/A$ is the scattering length, $\kappa = (m\epsilon)^{1/2}$, ϵ is the binding energy. We obtain from (2)

$$\Delta E = \frac{\operatorname{Re}A+\varkappa}{\operatorname{Im}A}\frac{\Gamma}{2}, \quad \Gamma = \frac{8\pi}{m}\frac{\operatorname{Im}A}{(A+\varkappa)^2}\overline{|\Psi(0)|^2}. \tag{3}$$

Formulas (3) give (for $\epsilon \approx 150–200$ MeV) $\Delta E \approx \Gamma$, if we set Re A = 0 and evaluate A starting with the value of Γ in accordance with formula (1). We can arrive at the same result by setting Im A = 0 and estimating Re A from the simplest pole diagrams (for example, the exchange of a ω meson in the annihilation channel). If Re A ≈ Im A, then, as follows from (3), the shift of the level (for sufficiently small ϵ) also in order of magnitude does not exceed Γ.

The quantities ΔE and Γ could also be calculated by finding the poles of the scattering amplitude for the complex BP potential. However, this approach is hardly more reliable since in the BP potential the exchange interaction (the exchange of virtual mesons in the s-channel) is not taken into account. As is shown by the estimates given above (the case Im A = 0) such an interaction may shift the level by an amount of the order of Γ.

In our calculations the binding energies and the wave functions were calculated by solving the Schrödinger equation for a real BP potential. The widths of the resonances were estimated by means of formula (1). In accordance with the foregoing considerations one can suppose that annihilation and exchange effects are able to shift the meson masses obtained by us by an amount of the order of the width of the level.

In the BP scheme the potential is assumed to be equal to zero at distances smaller than 0.6 F. We have verified that the nature of the cutoff (the introduction of attraction or repulsion equal in absolute value to the depth of the potential at 0.6 F) does not alter particularly strongly the binding energy of s-states (for which "zero cut-off" is least justified)—the relative shift of the level does not exceed the corresponding change in the scattering phase. The same situation also holds in the case of variations in the shape of the long range part of the potential which extends from 0.6 to 2 F (for example by replacing the BP potential by one or by several rectangular wells with the condition which places an upper bound in the number of s-levels in a monotonic potential, cf.,[6,7]). The BP potential contains spin-orbit and tensor forces. Estimates have shown that the contribution of the latter to the binding energy of states with a uniquely possible value of the orbital angular

[1)]For $p\bar{p}$-annihilation we have the value $(v\sigma_a)_{v\to 0} = 65$ mb. The number quoted in the text corresponds to $n\bar{p}$-annihilation (isospin I = 1).

Meson resonances

Theory					Experiment			
Notation	⟨ls⟩	Mass	$I^G(J^P)$	Width	Notation	Mass	$I^G(J^P)^C$	Width
$^{11}s_0$	0	1690	$0^+ (0^-)$	89				
$^{11}p_1$	−1	1777	$0^- (1^+)$	100				
$^{13}p_0$	−2	1289	$0^+ (0^+)$	57	D	1285±4	$0^+ (A)^+$	31±4
$^{13}d_1$ *	−3	1382	$0^- (1^-)$	71				
$^{13}p_1$	−1	1410	$0^+ (1^+)$	68	E	1424±6	$0^+ (0^-, 1^+)^+$	71±10
$^{13}s_1$ *	0	1414	$0^- (1^-)$	63				
$^{13}f_2$ **	−5	1572	$0^+ (2^+)$	107	f'	1514±5	$0^+ (2^+)^+$	73±23
$^{13}d_2$	−1	1608	$0^- (2^-)$	99				
$^{13}p_2$ **	+1	1620	$0^+ (2^+)$	88				
$^{13}g_3$	−5	1839	$0^- (3^-)$	148				
$^{31}s_0$	0	1722	$1^- (0^-)$	93	π_A	1633±9	$1^- (A)^+$	93±24
$^{31}p_1$	0	1814	$1^+ (1^+)$	104				
$^{33}p_0$	−2	1724	$1^- (0^+)$	105				
$^{33}s_1$ ***	0	1727	$1^+ (1^-)$	94	ρ_N	1650±20	$1^+ (N)^+$	120±30
$^{33}p_1$	−1	1771	$1^- (1^+)$	107				
$^{33}p_2$	+1	1850	$1^- (2^+)$	88				
$^{33}d_1$ ***	−3	1855	$1^+ (1^-)$	117	ρ	1700±20	$1^+ (\ )^-$	110±25

Note. ⟨ls⟩ = [J(J + 1)−l(l + 1)−S(S + 1)]/2 is the coefficient in the case of spin-orbit forces. $^{2I+1,\,2S+1}x_{2J+1}$ (x = s, p, d, f, g) are the spectroscopic symbol of the levels. Asterisks denote the mixed pairs of levels.

momentum is small (of the order of 10%). And with regard to the mixing of states with different orbital angular momenta (with the same values of the other quantum numbers), the value of this effect can be strongly affected by annihilation processes (due to the presence of common decay channels).

The results of the calculations are shown in the table (the left hand side). In the first column is shown the spectroscopic state symbol (the upper indices are respectively the isospin and the spin multiplicities), in the second column are shown the values of the spin-orbit factor which explain the obtained sequence of levels. The masses and the widths (the third and the fifth columns) are given in MeV. For the meson quantum numbers (the fourth column) the Rosenfeld notation[8] has been utilized (outside the brackets are given the isospin and the G-parity, inside the brackets are given the meson spin and parity). Among the 17 mesons contained in the table only three pairs have the same quantum numbers (these particles are denoted by asterisks). The mesons in these doublets, generally speaking, are mixed as a result of tensor forces and common annihilation decay channels.

In addition to the shift of the levels discussed above due to annihilation effects the masses enumerated in the table can undergo changes as the potential itself describing NN and $N\bar{N}$ scattering is made more precise. The least reliable in this respect are the s-states (the static variant of the BP potential describes the s-phases in $N\bar{N}$ scattering worse than the phases in other orbital states).

At the present time there exist experimental indications of the existence in the mass region under consideration (1280–1880 MeV) of 16 meson resonances. For only six of them at least one of the quantum numbers has been established. These six resonances are shown in the right hand side of the table.

We note that quite close to the mass region covered by the table we have the f(1260) meson with the quantum numbers 0^+ (2^+). In the table there appear two mesons ($^{13}f_2$ and $^{13}p_2$) with the same characteristics, but with much larger masses (1572 and 1620). Thus, if the estimate of the accuracy of our calculations ($\Delta E \approx \Gamma$) is correct, then it is most probable that the f-meson is not a "quasinucleus," i.e., it does not consist primarily of a nucleon and an antinucleon. At the same time, if the scheme proposed above is correct, then the f′(1515) meson must in actuality represent a doublet (the distance between the components is of order of or less than the width). Experimentally this fact can manifest itself in an anomalous (a non Breit-Wigner) line shape (cf.,[9-11]). In the table there is no place for the A_2-meson if its isospin is equal to 1 (there is available a doublet close to it in mass with the quantum numbers 0^- (1^-)).

We emphasize that in view of the indefiniteness indicated above in the theoretical values of the masses, and also due to the incompleteness of the experimental data the identification proposed in the table of the predicted and the observed resonances should be regarded as highly preliminary.

From the scheme proposed above it follows that the ratios of the partial widths for the decay of meson resonances must reproduce the variation of the relative probabilities for the different channels for the annihilation of the $N\bar{N}$ system from states of the continuous spectrum with appropriate quantum numbers. A comparison of the data on annihilation in s-states[12] with the partial widths of the π_A (1640) and ρ_N (1650) mesons qualitatively confirms this prediction (we note that the accuracy of the experimental values is very poor).

In addition to the bound states enumerated in the table the quasinuclear model also predicts the existence of a number of mesons with masses greater than 2m. This can be seen most simply from a consideration of nonrelativistic Regge trajectories. The wave functions of the bound states obtained by us have no radial modes. Therefore, the family of trajectories under consideration is characterized by only three parameters—the isospin, the total spin of the nucleons and the number

$S' = l - J = 0, +1$. It can be easily seen that all the mesons distribute themselves along eight Regge trajectories. Along each of them the total angular momentum of rotation of the bound state (J) increases as the meson mass increases. Near the threshold for the decay into N and $\overline{N}$ the trajectory turns downwards.

The resonances above the threshold must manifest themselves in $N\overline{N}$ scattering, and in the potential model the partial width of the channel for elastic scattering is determined in order of magnitude by the expression $\Gamma_{NN} \approx \hbar^2/mR^2$, and this for $R \approx 1.5-2$ F amounts to 20–10 MeV (more accurate values of Γ_{NN}, and also of the meson masses in the region beyond the threshold will be communicated in another paper).

At the present time there exist experimental indications of the existence of eight resonances with masses exceeding 2m, and five of them have manifested themselves in the cross sections for the $N\overline{N}$ interaction[8]. However, these data so far are too indefinite and a comparison of them with the predictions of the model proposed above would be premature.

From all the above one can draw the following conclusions:

1. It is shown that the hypothesis of the quasinuclear nature of heavy meson resonances does not contradict the presently available data on the NN and $N\overline{N}$ interaction.

2. The model predicts the existence of a comparatively large number of heavy mesons with low spins. The available experimental information on meson resonances does not contradict these predictions, but for more definite conclusions considerably more precise and extensive experimental data are required. It is of particular importance to establish the quantum numbers, and the number of times they are repeated and to measure the partial widths for resonances above the threshold.

In conclusion we note that an analogous potential approach is possible, in principle, also in the theory of heavy baryon resonances of mass of the order of 3m (the nonrelativistic three-particle system $NN\overline{N}$).

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