Resonant long-range interaction in hadronic systems and the quasinuclear nature of narrow low-lying dibaryons

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It is shown that the baryon-meson strong interaction in particle systems consisting of nucleons and Δ-isobars leads to a strong long-range attraction. This attraction arises because of the small virtuality of the intermediate $\pi\pi NN$-states in $N\Delta$-pairs and produces the spectrum of strongly-bound quasi-nuclear states whose decay in the $NN\pi$-channel is forbidden by energy conservation, whereas strong decays in the NN-channel are forbidden because of the Pauli principle, so that the corresponding widths have the electromagnetic scale of ~ 0.1 keV. Experimentally accessible predictions are reported for the masses, quantum numbers, and form factors of dibaryon and more complex systems. The existence of stable states in systems with maximum values of isospin and the absolute magnitude of its z-component are discussed.

The effective-mass spectra of pp-systems has been found in recent years to contain statistically significant narrow peaks (see Refs. 1 and 2 and the references therein) that can be regarded as direct evidence for the excited states of the dibaryon (BB) system (Fig. 1). Typically, the widths of the resonances are unexpectedly small for hadronic systems ($\Gamma < 1$ MeV), the masses are low $M_{BB} < M_{NN\pi} = 2m_N + m_\pi = 2015$ MeV, and the spectra of these excitations begin almost at the NN-threshold ($M_{NN} = 2m_N \approx 1880$ MeV): $M_{BB} \gtrsim 1900$ MeV for a mean level separation of about 10 MeV, which is also anomalously small on the scale of the hadronic world.

In contrast to existing theoretical studies in this area, which are based on dynamic quark models and phenomenological approaches,[2-6] we use the baryon-meson strong-interaction dynamics to investigate for the first time the possibility of a previously ignored but important mechanism of hadronic mechanics, namely, resonant long-range interaction that amplifies the 2π-exchange amplitudes for small momentum transfers ($|\mathbf{q}|^2 \ll m_\pi^2$) in systems consisting of nucleons and Δ-isobars. The resonant long-range interaction in $N\Delta$-systems develops because of the uniquely low virtuality

$$\mu_{N\Delta}=2m_\pi-(\mathrm{Re}\, m_\Delta-m_N)\approx 10\ \mathrm{MeV}\ll m_\pi,\ \Gamma_\Delta \qquad (1)$$

in the intermediate $NN\pi\pi$, $\Delta'\Delta'$, and $N\Delta'\pi$ states of the 2π-exchange amplitudes (Fig. 2). This is in contrast to the NN-interaction in which the virtuality of the intermediate 2π-exchange states is

$$\mu_{NN}\approx 2m_\pi+\mathrm{Re}\, m_\Delta-m_N\approx 560\ \mathrm{MeV}$$

(m_N, m_Δ, m_π are, respectively, the masses of the nucleon, the Δ-isobar, and the pion). The resonant $N\Delta$-interaction that arises in this way is a general consequence of the quantum-mechanical uncertainty relation, and manifests itself formally in that the energy denominators corresponding to the cross diagrams with intermediate $NN\pi\pi$ states and rectangular diagrams with intermediate $N\Delta'\pi$ states acquire a dependence $\sim q^2$ on the transferred momentum q after integration with respect to momentum within a loop, which is typical for the Coulomb potential. A relatively simple, but sufficiently rigorous, qualitative analysis of the onset of the resonant long-range interaction can be performed within the framework of the Lee model,[7] which assumes a particularly clear form in the nonrelativistic version of the model.[8]

The most interesting hadronic system in which the resonant long-range interaction should develop and predominate because of strong πN and $\pi\Delta$ coupling is probably the $N\Delta$ system. Dynamic analysis of this system with a view to a possible interpretation of low-lying dibaryon resonances as quasi-nuclear bound $N\Delta$ states is of particular interest because of the possibility of an experimental verification of the role of the resonant long-range interaction in the evolution of narrow quasi-nuclear excitations of hadronic systems consisting of nucleons and Δ-isobars.

There is also comparable interest in the analysis of the possible resonant long-range interaction in more complicated systems that include K, ρ, and ω mesons, hyperons, and other hadrons, and also atoms and molecules. However, this range of problems, and also the evaluation of the 2π-exchange potential lie outside the framework of the present paper because it is essentially the semi-qualitative and semi-phenomenological stage of an analysis whose aim is to look for observable situations that can be predicted by the baryon-meson theory. We shall therefore confine our attention to the one-boson exchange potential (OBEP) that has been successful in the analysis of NN data by approximating the

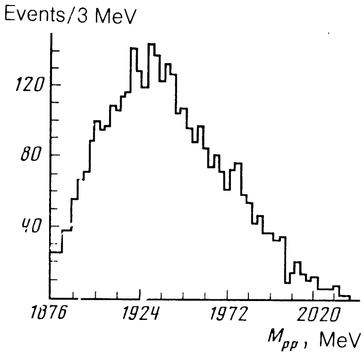

FIG. 1. Effective mass spectrum of the two protons in the $np \to pp\pi^-$ reaction with $P_n = 1.257$ GeV/c (Ref. 1).

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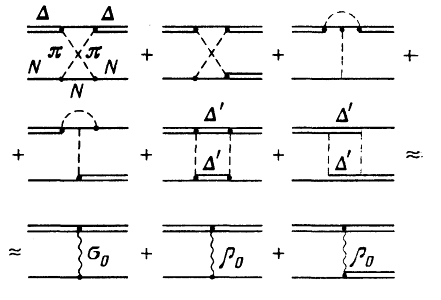

FIG. 2. The 2π-exchange amplitudes for the $N\Delta$-system, which provide the dominant contribution for small momentum transfers.

sums of nonresonant 2π-exchange amplitudes by the exchange of massless scalar-isoscalar and vector-isovector effective σ_0 and ρ_0 mesons [$m_{\sigma_0} \approx m_{\rho_0} \approx 0$ by virtue of (1)], which leads to the Coulomb potential in the $N\Delta$ system. The coupling constants between σ_0, ρ_0 and N, Δ can be expressed in terms of their known values in the NN-channel, determined from the NN phase shifts with allowance for the nonresonant 2π-exchange ($g^2_{\sigma NN} = 5.7$ and $g^2_{\rho NN} = 0.55$) and without this exchange ($g^2_{\sigma NN} = 9.2$ and $g^2_{\rho NN} = 0.95$) (Ref. 9):

$$g^2_{\sigma_0 NN} = 9.2 - 5.7 = 3.5, \qquad g^2_{\rho_0 NN} = 0.95 - 0.55 = 0.4.$$

In addition, using the fact that $f^2_{\pi N\Delta} \approx 1.5 f^2_{\pi NN}$ (Ref. 10), we obtain

$$g^2_{\sigma_0 N\Delta} \approx 3.5 \cdot (1.5)^2 \approx 7.9, \qquad g^2_{\rho_0 N\Delta} \approx 0.4 \cdot 1.5 \approx 0.6.$$

The only free phenomenological parameter is then the scale on which the asymptotic behavior of the Coulomb $N\Delta$-potential breaks down at short distances, where the attraction becomes a repulsion. The point at which the potential changes sign (radius of the core) will be denoted by r_c: $V_{N\Delta}(r_c) = 0$.

The restriction of the validity of the Coulomb asymptotic behavior at large distances, due to the fact that $\mu_{N\Delta} \approx 10$ MeV $\neq 0$, will be insignificant from now on, because we shall confine our attention to low-lying $N\Delta$-states whose root mean square radius is $\langle r^2 \rangle^{1/2} \ll \mu^{-1} \approx 20$ fm. The potential of the repulsive core can then be conveniently taken to be $1/r^2$, which leads to an analytic solution of the spectral problem. Using the static OBEP approximation and the expansion $\exp(-\mu r) \approx 1 - \mu r$, we thus obtain the following expression for the $N\Delta$-potential:

$$V_{N\Delta}(r) = g^2 r_c (1 - \mu r_c)/r^2 - g^2/r + g^2 \mu, \tag{2}$$

where

$$g^2 = g_0^2 - 4\langle \mathbf{I}_N \mathbf{I}_\Delta \rangle g_1^2, \quad g_0^2 = g_{\sigma_0 NN} g_{\sigma_0 N\Delta} \approx 5,$$
$$g_1^2 = g^2_{\rho N\Delta} \approx 0{,}6, \quad r_c \approx m_\pi^{-1} = 1.4 \text{ fm}. \tag{3}$$

The mass spectrum of the $N\Delta$-system with the potential (2) is determined by three quantum numbers, namely, I (isospin), n_r (radial excitation), and l (orbital angular momentum), and is degenerate in J, S, J_3, and I_3. It satisfies the mass formula

$$M(I, n_r, l) = m_N + \mathrm{Re}\, m_\Delta - m g^4/2n^2, \tag{4}$$

where

$$m = m_N \,\mathrm{Re}\, m_\Delta/(m_N + \mathrm{Re}\, m_\Delta),$$
$$n = n_r + [2g^2 m r_c (1 - \mu r_c) + (l + {}^1/_2)^2]^{1/2} + {}^1/_2,$$

in which the three parameters g_0, g_1, and r_c have a clear physical interpretation and perfectly definite values (3). The repulsive core potential produces a significant lifting of the accidental Coulomb degeneracy in $n_r + l =$ const, and the hyperfine J and S splitting of the levels, which occurs under the influence of nonstatic effects (spin-orbit and tensor forces), is small in comparison with the mean separation between low-lying levels, and can be calculated from perturbation theory:

$$\Delta M_{LS} = -{}^1/_8 (g_0^2 + 12 g_1^2 \langle \mathbf{I}_N \mathbf{I}_\Delta \rangle) \langle \mathbf{LS} \rangle m^{-2} \langle r^{-3} \rangle \approx 1 \text{ MeV},$$
$$\Delta M_T = -g_1^2 \langle \mathbf{I}_N \mathbf{I}_\Delta \rangle \langle \hat{S}_{12} \rangle m^{-2} \langle r^{-3} \rangle \approx 1 \text{ MeV},$$

where

$$\hat{S}_{12} = (\mathbf{S}_N \mathbf{r})(\mathbf{S}_\Delta \mathbf{r})/r^2 - \mathbf{S}_N \mathbf{S}_\Delta/3.$$

When hyperfine splitting is taken into account, we thus obtain

$$M(I, n_r, l, S, J) = M(I, n_r, l) + \Delta M_{LS} + \Delta M_T.$$

The best agreement with the measured positions of the

TABLE I. Isospin I, radial quantum number n_r, orbital angular momentum quantum number l, mass M, and root mean square radius $(\langle r^2 \rangle)^{1/2}$ for the lower part of the spectrum of quasi-nuclear states of the $N\Delta$-system, calculated for $g_0^2 = 5.0$, $g_1^2 = 0.6$, $r_c = 1.3$ fm, $m_N = 940$ MeV and $\mathrm{Re}\, m_\Delta = 1220$ MeV (Ref. 11). Only the lowest twenty five states are listed.

In_rl	M_{BB}, MeV	$\langle r^2 \rangle^{1/2}$, fm	M_{exp}, MeV [1]	In_rl	M_{BB}, MeV	$\langle r^2 \rangle^{1/2}$, fm	M_{exp}, MeV [1]
100	1895	3.2	–	122	2003	6.4	–
101	1903	3.4	1901	106	2003	5.4	–
102	1919	3.6	1923	123	2013	6.8	–
103	1939	3.9	1933	115	2014	6.4	–
110	1950	4.6	1942	130	2020	7.5	–
111	1956	4.7	1959	107	2022	6.1	–
104	1961	4.3	1965	131	2023	7.7	–
112	1967	4.9	1968	124	2025	7.4	–
113	1982	5.3	1979	132	2029	8.0	–
105	1983	4.8	–	116	2030	7.1	–
120	1990	6.0	–	133	2037	8.5	–
121	1995	6.1	–	125	2038	8.1	–
114	1998	5.8	–				

peaks in the effective mass spectrum (see Table) is given by the mass formula (4) for $g_0^2 = 5$, $g_1^2 = 0.6$, $r_c = 1.3$ fm. These parameter values are practically the same as those given in (3) in the OBEP model. The lowest level $M_{100} = 1895$ MeV is probably too weakly excited in the $np \to pp\pi^-$ reaction at the neutron momentum $P_n \approx 1.5$ GeV/c, and cannot be seen in the effective mass spectrum with existing statistics. However, its existence is indirectly confirmed by the "knee" on the energy dependence of the total pp-scattering cross section at the energy that is exactly equivalent to its mass. This "knee" looks even more convincing (Fig. 3) when it is taken in conjunction with the peak on the total cross sections at $M_{101} = 1903$ MeV (Ref. 2).

It is clear from the Table that, below 1980 MeV, the above model associates definite quantum numbers and wave functions with each peak in the effective mass spectrum. The absence of experimental evidence for the levels predicted by the model above 1980 MeV is probably due to the fact that the effective mass spectrum falls rapidly with increasing M (see Fig. 1). The peaks were not statistically significant in this region (with the present statistics), and were discarded in the analysis.

The model gives an unambiguous prediction for the isospin of low-lying resonances $I = 1$, since $I = 0$ is not realized when the N and Δ isospins are combined ($\frac{1}{2} + \frac{3}{2} = 1$ or 2), and the masses of states in the $I = 2$ multiplet are close to the $NN\pi$-threshold (the lowest level with $I = 2$ has $M = 2062$ MeV), so that when the uncertainty in the parameters g_0^2 and g_1^2 is taken into account, it may well turn out that this level is actually below the threshold.

The model predicts two possible spin values, namely, $S = 1$ and $S = 2$. For $M_{BB} < M_{NN\pi}$, the latter always corresponds to a narrow resonance because the total spin $\hat{S}^2 = (S_N + S_\Delta)^2$ is strictly conserved by the strong interaction in the two-body system, while the spin of the NN-system is not equal to 2, and decay can occur mostly under the influence of the electromagnetic interaction. For $S = 1, I = 1$, the Pauli principle ensures that only odd values of l are possible

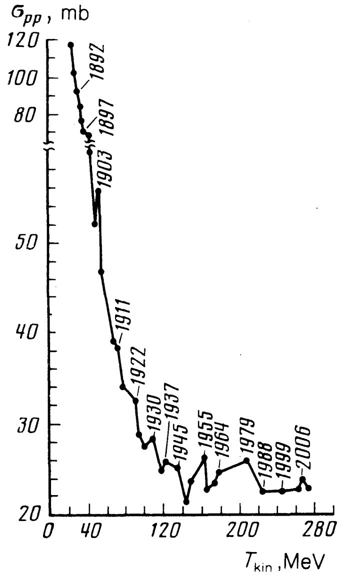

FIG. 3. The pp-scattering cross section as a function of the kinetic energy in the laboratory frame.[12]

in the NN-system, so that all the $N\Delta$-states with $S = 1, I = 1$ and even l decay under the influence of the electromagnetic interaction.[5] According to Ref. 4, their widths then amount to ~ 0.1–1 keV.

The two lowest $N\Delta$-states that are spin-degenerate and have $I = |I_3| = 1$, $n_r = l = 0$, and $S = 1$ or 2 do not then undergo strong decays ($N\Delta(S=1) \to pp\gamma$, $N\Delta(S=2) \to pp$, $pp\gamma$), whereas the next levels with $l = 1$ and $S = 1$ can decay strongly into the pp-channel with the width $\Gamma_s \sim [\Gamma_\Delta(M - 2m_N)]^{1/2} \approx 50$ MeV. Hence, in more complicated $N\Delta$-systems, e.g., $NN\Delta$ etc., in which spin reversal and changes in orbital angular momenta due to the strong interaction are possible, the S-wave states whose strong decay depends on the P-wave impurity in the $N\Delta$-pair are the only narrow states. The magnitude of this impurity should have the typical nuclear scale of about 1%, which suggests that the width of the three-proton decay of the ground state of $NN\Delta$-system is $\Gamma_{NN\Delta} \sim 0.01 \times \Gamma_s \approx 0.5$ MeV.

When the ground-state mass of the $NN\Delta$-system is estimated, it is important to remember that the resonance potential acts only in one $N\Delta$-pair. This is because of the change in the state of the source of $\pi\pi$-pairs (Δ-isobars) during the interaction process. As a result, the nucleon that is not part of the resonant pair should have a binding energy that is almost the same as that of the deuteron (approximately 1 MeV). This leads to the following estimate for the mass spectrum of the S-wave bound states, whose levels differ by radial excitations of the resonant $N\Delta$-pair:

$$M_{NN\Delta}(n_r) \approx M_{N\Delta}(n_r, l=0) + m_N$$

$$\approx 3m_N + \begin{cases} 15\ \text{MeV}, & n_r = 0 \\ 70\ \text{MeV}, & n_r = 1 \\ 110\ \text{MeV}, & n_r = 2 \\ 140\ \text{MeV}, & n_r = 3 \end{cases}.$$

These $NN\Delta$-states should decay preferentially into two fast (in the center of mass system) protons and one slow proton. Experimental evidence for the decay of such states, but with greater mass, is reported in Ref. 13.

The formation and decay of three-baryon resonances (BBB) can be investigated in detail in nuclear reactions at 10–300 MeV/nucleon, the simplest of which are

$$p + {}^3\text{He} \to (BBB)^{+++}_{I=3/2} + n, \qquad n + {}^3\text{H} \to (BBB)^{0}_{I=3/2} + p,$$

$${}^3\text{He} + {}^3\text{He} \to (BBB)^{+++}_{I=3/2} + {}^3\text{H}.$$

Analysis of quasi-nuclear $\Delta\Delta$-systems shows that the masses of $I = 0$ states with $g_0^2 = 5.5$, $g_1^2 = 0.5$, and $r_c = 1.3$ fm lie near the $NN\pi$ threshold (or even just below this threshold) and include narrow states whose strong decay into the np-channel is forbidden by selection rules. The possible existence of stable states whose decay is forbidden by the conservation of the z-component of isospin presents an interesting problem. For example, $(BB)^-$ and $(BB)^{+++}$ states with $I \geqslant 2$ and mass $M < 2m_N + m_\pi$ can only undergo weak decays.[4,14]

Finally, we note that it may be possible to investigate the characteristic γ-rays from transitions between fine and hyperfine structure levels of the above resonances, with mean level separations of 10 and 0.4 MeV, and 6–10 levels per band. Such resonances may be excited not only in hadronic but also electromagnetic interactions ($\gamma\gamma'$; ee').

The large values of $\langle r^2 \rangle^{1/2}$ in the Table are of particular interest because, on the one hand, practically all the experimentally observed quantities depend directly or indirectly upon them and, on the other hand, they indicate the dominance of the resonant long range interaction in quasinuclear $N\Delta$-systems. Moreover, the model predicts the characteristic alternation of the quantum numbers of low-lying levels, including their hyperfine structure. This alternation can be checked experimentally.

We note in conclusion, that the successful description of all the known properties of narrow low-lying dibaryon resonances in the terms of the above resonant long-range interaction mechanism, which leads to the formation of quasi-nuclear $N\Delta$-systems with excitation energy of 10–70 MeV/nucleon and width of 10^{-3}–10^{0} MeV, suggests that these resonances can play the part of "hydrogen atoms" that are the starting point of the resonance physics of highly-excited quasi-nuclear hadronic systems and media.

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