Theoretical interpretation of experimental dibaryon resonance data

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Theoretical predictions of dibaryon resonances based on quark bag models are discussed together with possible experimental manifestations of these resonances. The predicted peaks might be seen as poles of the P-matrix rather than peaks in the cross sections. The resonance interpretation of the peaks observed in the NN-system is complicated by the presence of pseudoresonances.

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Makarov, in his paper entitled "Dibaryon resonances" (published in this issue), reviews the experimental situation and mentions only briefly the theoretical papers in this field. Here we shall discuss three principal aspects of dibaryon resonances, namely, (1) theoretical predictions of these resonances, (2) how the predicted resonances will appear in experiment, and (3) how experimental data can be used to distinguish between a genuine resonance and a peak of some other nature.

(1) Since we are concerned with energies of 300–500 MeV above the NN-threshold, the most appropriate approach to the problem is the quark-gluon bag model, which has been successful in the single-baryon and boson sectors.[1]

Two-baryon states and exotic mesonic states were predicted in Refs. 2 and 4, but it was already clear in the first paper on the MIT model[1] that the six-quark dibaryon bags and four-quark exotic mesonic bags were described on the same basis as the single-baryon bags. It is precisely these considerations that have provided the main stimulus to experimental searches for dibaryon resonces.

However, up to 1979, all searches for exotic resonances (for example, $\pi\pi$ with isospin $I=2$) and dibaryon NN-resonances in the S-state were unsuccessful. Moreover, experimental phase shifts clearly indicate the presence of repulsion and the absence of any structure in the predicted energy range.

An important paper was published in 1979 by Jaffe and Low[5] who showed that the states predicted by the bag model need not necessarily appear as resonance peaks. When the coupling between the bag state and the open hadronic channel is strong, the pole that appears at the energy of this state belongs not to the S-matrix but to the so-called P-matrix which is uniquely related to the S-matrix.

Analysis of the $^3S_1$ and $^1S_0$ phase shifts, reported in Ref. 6 for $T_{lab} > 300$ MeV, shows the presence of a pole in the P-matrix at $M = 2.08$ and 2.11 GeV, respectively. These numbers must be compared with theoretical predictions,[2] namely, $M = 2.165$ and 2.24 GeV, i.e., there is excellent agreement. It is important to note, however, that the bag model used in Ref. 2 is semi-empirical and the precision of the theoretical predictions is not entirely clear. For example, the $\Lambda\Lambda$ bound state predicted in Ref. 2 has not been confirmed experimentally. It is possible that the $\Lambda\Lambda$ bag state in fact lies above the $\Lambda\Lambda$ threshold and, as in the case of S-waves in the NN-system, appears in the form of a pole in the P-matrix rather than the S-matrix.

Simonov has recently proposed[7] a dynamic model of coupled hadronic and quark channels in an attempt to justify the P-matrix analysis,[5] and achieved excellent agreement with S-phases in NN-scattering throughout the range $0 \leq T_{lab} \leq 515$ MeV, using only three parameters, namely the residue and the position of the pole of the bag S-state in the P-matrix and the position of the deuteron (singlet deuteron) pole in the S-matrix. This analysis also demonstrates the importance of bag states in the dynamics of the NN-interaction. For example, it is shown in Ref. 7 that the broad bag state corresponds to hard-core repulsion in which the phase shift falls linearly with energy.

What can be said about the NN-resonances in higher-order waves? There are predictions[2,3] of six-quark dibaryon resonances with quantum numbers $J^P = 1^+$, 2^+, 3^+ (in which all quarks are in the S-state) in the mass range 2.16–2.5 GeV and above.

The predictions for negative-parity states are not, however, very reliable because there is as yet no consistent theory of rotating bags. This would require an initial examination of the deformed bag, followed by the introduction of rotation, i.e., it would involve dynamic variables corresponding to the deformed rotating walls of the bag. This problem has not been solved, and the precision of theoretical predictions for the level energies of a bag with nonzero angular momentum is not known.

Unfortunately, the theory does not predict the strength of the coupling between the six-quark states and the outer NN-channel, so that we cannot say in advance whether a given state corresponds to a pole in the S-matrix (and the apparent peak in the cross section), or whether the pole is only in the P-matrix and there is no peak in the cross sections, which is characteristic for strong coupling. The presence of the centrifugal barrier weakens the coupling of the outer hadron and the bag channels, and may lead to a resonance (pole in the S-matrix). An example of this situation is provided by the ρ-meson where, however, the coupling to the 2π-channel is additionally weakened by the different quark compositions of the 2π and ρ.

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Whatever the case might be, any bag state gives rise to a pole in the P-matrix, so that the experimental analysis can be made specifically in terms of the P-matrix if the phase shifts are known. Preliminary examination of experimental phase shifts[8] shows that the P-matrix does in fact have poles in all the P- and D-states.

Therefore, as far as points (1) and (2) above are concerned, we may summarize as follows: the bag model predicts numerous states for masses $M \gtrsim 2.1$ GeV, which should appear as poles in the P-matrix and, in some cases (when the coupling to hadrons is weak), as poles in the S-matrix as well, i.e., as true resonances producing peaks in cross sections.

(3) In the preceding review (and in most papers in this field) the question of experimental criteria for the identification of a given irregularity with a true resonance (corresponding to a pole in the S-matrix) has been virtually ignored. The usual definition of a resonance is more pragmatic: a resonance is considered to be any observed peak to which definite quantum numbers can be assigned. The definition of a resonance has become a more acute problem, specifically in the dibaryon situation, since the discovery of pseudoresonances.[9] Pseudoresonances are peaks or irregularities that are due not to S-matrix poles but to open inelastic channels, most commonly a quasi-two-particle channel (resonance plus particle). It has long been known that irregularities occur in the case of strong coupling to an opening inelastic threshold but, in addition, it was shown in Refs. 9 and 10 that pseudoresonances correspond to the same Argand diagrams for partial amplitudes as genuine resonances. It follows that the looping criterion which has been considered as particularly effective on the partial Argand diagram does not in fact work, since it does not distinguish between resonances and pseudoresonances. It has been shown[10,11] that if the Argand diagram is constructed for the forward-scattering amplitudes and then, separately, for a particular angle (for example, for the back-scattering amplitude), it turns out that the forward and backward loop radii are equal for genuine resonances, but very different for pseudoresonances. This was used to demonstrate the presence of pseudoresonances in the KN system and of genuine resonances in the $\bar{K}N$ system.[10] As far as the dibaryon system is concerned, it was shown in Ref. 11 for the πd amplitude that a pseudoresonance is present in the neighborhood of the NΔ threshold, and this is so both on the theoretical and experimental curves. Moreover, a strict upper limit was imposed on the possible contribution of the resonance, namely, $\Gamma_{\pi d}/\Gamma_{\text{tot}} < 0.1$. Unfortunately, the phenomenon of pseudoresonances is quite common in dibaryon systems. The reason is that the inelasticity increases rapidly in the region $p_{\text{lab}} \sim 1.2$ GeV/c. As noted above, pseudoresonances are definitely present in the $I = 1$ channel in the πd and the NN systems (see Ref. 12), and very probably in the $I = 0$ channel as well. Therefore, the problem is that of detecting resonances against the background of pseudoresonances, which is not at all simple since pseudoresonances correspond to irregularities in the cross sections and a loop on the Argand diagram for many partial waves at once, and the resonances predicted by the bag theory also have very similar masses for neighboring partial waves.

Moreover, data on baryonium (resonances in the $N\bar{N}$ system, which were seen in most experiments prior to 1979, but vanished when improved experiments were performed both below and above the $N\bar{N}$ threshold; see the review and experimental papers in Ref. 13) suggest that the resonance interpretation of irregularities in cross sections must be approached with extreme caution.

There are several ways of escaping from the dilemma. Firstly, as already noted above, one can investigate Argand diagrams for the NN-amplitudes at different angles, and compare loop radii for different angles. The most complete recent analysis by Arndt *et al.*[14] appears to confirm that this is possible. Secondly, one can look for poles in the P-matrix as was done in Refs. 6 and 7 for the S-waves. Thirdly, one can try to determine directly the poles of the S-matrix, by analytically continuing the parametrized experimental data into the complex plane.

The last method was successfully employed in a very recent paper[15] in which use was made of the phase-shift analysis[14] of NN-scattering in $^1D_2$ and $^3F_3$ states. The phase shifts were parameterized with the aid of the K-matrix and were continued into the complex energy plane. Coupled NN and NΔ channels were taken into account, so that threshold singularities could be written down explicitly. The resonances were thus found to lie at $\sim(2.15 - i0.06)$ GeV. This is the most successful attempt so far to determine the parameters of the dibaryon resonance. The only objection to this procedure is that the expansion of the K-matrix into a series and its representation by a finite polynomial[15] is valid only within the circle of analyticity, which is bounded by the nearest singularities that have not been taken into account, and the latter are known[9,10] to lie at the same distance as the above resonance. It is possible, however, that allowance for these singularities will not result in a strong shift of the position of the resonance. There is no doubt that much new and interesting information on dibaryon resonances will emerge in the near future.

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