

Influence of a $Z^+(1540)$ resonance on K^+N scattering

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The impact of a ($I=0, J^P=\frac{1}{2}^+$) $Z^+(1540)$ resonance with a width of 5 MeV or more on the $K^+N(I=0)$ elastic cross section and on the P_{01} phase shift is examined within the KN meson-exchange model of the Jülich group. It is shown that the rather strong enhancement of the cross section caused by the presence of a Z^+ with the above properties is not compatible with the existing empirical information on KN scattering. Only a much narrower Z^+ state could be reconciled with the existing data—or, alternatively, the Z^+ state must lie at an energy much closer to the KN threshold.

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Recently the LEPS Collaboration at Spring-8 presented evidence for the existence of a narrow baryon resonance with strangeness $S=+1$ [1]. In the following, four other collaborations from different laboratories announced the observation of a similar structure in their experiments [2–5]. The observed structure was immediately brought into connection with an exotic pentaquark state called Z^+ whose existence had been proposed since long time in the context of different quark models.¹ Specifically, the resonance parameters with a peak position around 1540 MeV and a width around 20 MeV, extracted from these experiments, lie convincingly close to a theoretical prediction based on the chiral quark-soliton model of Diakonov *et al.* [6], who had proposed the existence of a Z^+ state with a mass around 1530 MeV and a width of around 15 MeV. Due to its quantum numbers, $S=+1, I=0$, and $J^P=\frac{1}{2}^+$, their Z^+ state can only decay (hadronically) into the K^+n or K^0p channels.

First cautious words about this interpretation were, however, raised by Nussinov [7] soon after the experimental result [1] was published. He pointed out that the existence of such a Z^+ state at around 1540 MeV should also be seen in the available K^+d scattering data. Though some “intriguing fluctuations” exist in the total K^+d cross section in the energy range which corresponds to KN cms energies of 1500–1600 MeV [7] Nussinov’s conclusion was that the lack of a prominent Z^+ signature in K^+d collisions restricts the width of the Z^+ to be smaller than 6 MeV. Similar but even more restrictive conclusions were drawn not long afterwards by Arndt and Collaborators [8]. These authors reexamined the available K^+N scattering data basis with the aim of exploring the possibility of accommodating a Z^+ -like resonance structure in their partial wave analysis. In an earlier analysis of the same data by the VPI group [9] this resonance has not been explicitly considered. The work of Ref. [8] confirmed that the existing K^+N data exclude Z^+ widths beyond the few-MeV level. Indeed their results even suggest that a Z^+ around 1540 MeV should have a width of $\Gamma=1$ MeV or even less in order to be compatible with the K^+N and K^+d data bases.

¹We follow the historical nomenclature adopted in the particle data tables. More recently, the resonance is being called Θ^+ .

In the present note we use the Jülich meson-exchange model for the KN interaction to investigate the effect of including in the model a Z^+ -like resonance structure on the description of the experimental data. Within a realistic potential model the open parameters are fixed by a simultaneous fit to all KN partial waves and therefore the contributions to the P_{01} channel (we use the standard spectral notation $L_{I, 2J}$), which provide the background for the $Z^+(1540)$ resonance, are strongly constrained by the empirical information in the other partial waves, and that means also from the other isospin channel. Furthermore, the use of a model allows one to produce a resonance structure from a bare pole interaction by dressing the bare baryon-meson vertex, with a width generated from self-energy loops, i.e., the nonpole and the pole part of the reaction amplitude can be treated consistently.

A detailed description of the Jülich KN model can be found in Refs. [10,11]. The model was constructed along the lines of the (full) Bonn NN model [12] and its extension to the hyperon-nucleon (YN) system [13]. Specifically, this means that one has used the same scheme (time-ordered perturbation theory), the same type of processes, and vertex parameters (coupling constants and cutoff masses of the vertex form factors) fixed already by the study of these other reactions.

The diagrams considered for the KN interaction are shown in Fig. 1. Obviously the Jülich model contains not only single-meson (and baryon) exchanges [Fig. 1(a)], but also higher-order box diagrams involving NK^* , ΔK , and ΔK^* intermediate states [Fig. 1(b)]. Based on these diagrams a KN potential V is derived, and the corresponding reaction amplitude T is then obtained by solving a Lippmann-Schwinger-type equation defined by time-ordered perturbation theory:

$$T = V + VG_0T. \quad (1)$$

From the reaction amplitude T phase shifts and observables (cross sections and polarizations) can be obtained in the usual way.

In the present investigation we use the KN model I described in Ref. [11]. (Note that we have performed also exploratory calculations with the other models in Refs. [11,14] and we obtained essentially the same results.) Results for phase shifts and also for cross sections and polarizations can

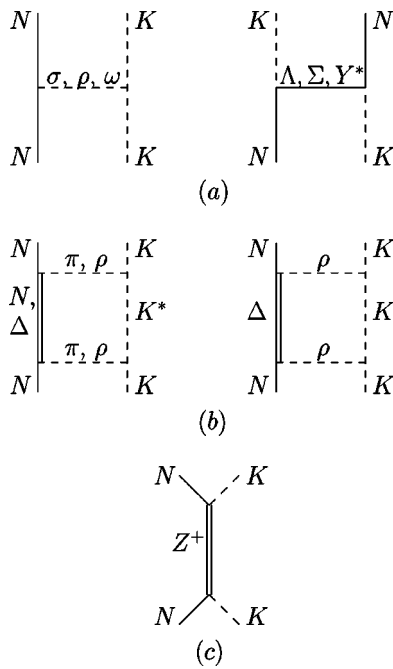


FIG. 1. Meson-exchange contributions to the KN interaction. Diagrams (a) and (b) define the original Jülich model I [10,11] that we use in the present investigations. Diagram (c) represents the considered $Z^+(1540)$ contribution.

be found, e.g., in Ref. [11]. Evidently, this model yields a good overall reproduction of all presently available empirical information on KN scattering. Specifically, it describes the data up to beam momenta of $p_{lab} \approx 1$ GeV/c, i.e., well beyond the region of the observed $Z^+(1540)$ resonance structure which corresponds to the momentum $P_{lab}=0.44$ GeV/c. Thus, this model provides a solid basis for studying the influence of the $Z^+(1540)$ resonance on the KN observables. As already emphasized above, the parameters of the model are fixed by a simultaneous fit to all KN partial waves and therefore the contributions to the P_{01} channel, where the Z^+ pentaquark state is supposed to occur [6], are constrained by the empirical information in the other partial waves.

The $Z^+(1540)$ resonance is included in the model by adding a pole diagram, as depicted in Fig. 1(c), with a bare mass $M_{Z^+}^{(0)}$ and a bare coupling constant $g_{KNZ^+}^{(0)}$ to the other diagrams that contribute to V . When this interaction is then iterated in the Lippmann-Schwinger equation (1), the KNZ^+ vertex gets dressed by the nonpole part of the interaction and the Z^+ acquires a width and also its physical mass via self-energy loops. For the present investigation we prepared two different models, one with a width of 20 MeV (as found in the experiment [3]), and one with a width of just 5 MeV, which was given in Ref. [15] as the most favorable width of the chiral quark-soliton model, and which corresponds roughly to the upper limit given in the paper by Nussinov [7]. The width of the Z^+ and also the resonance mass are calculated from a speed plot, but we must say that for such a narrow structure the resonance position basically coincides with the energy where the phase passes through 90 deg. Note that the bare mass and bare coupling constant are free parameters that are used to adjust the desired physical mass and width of

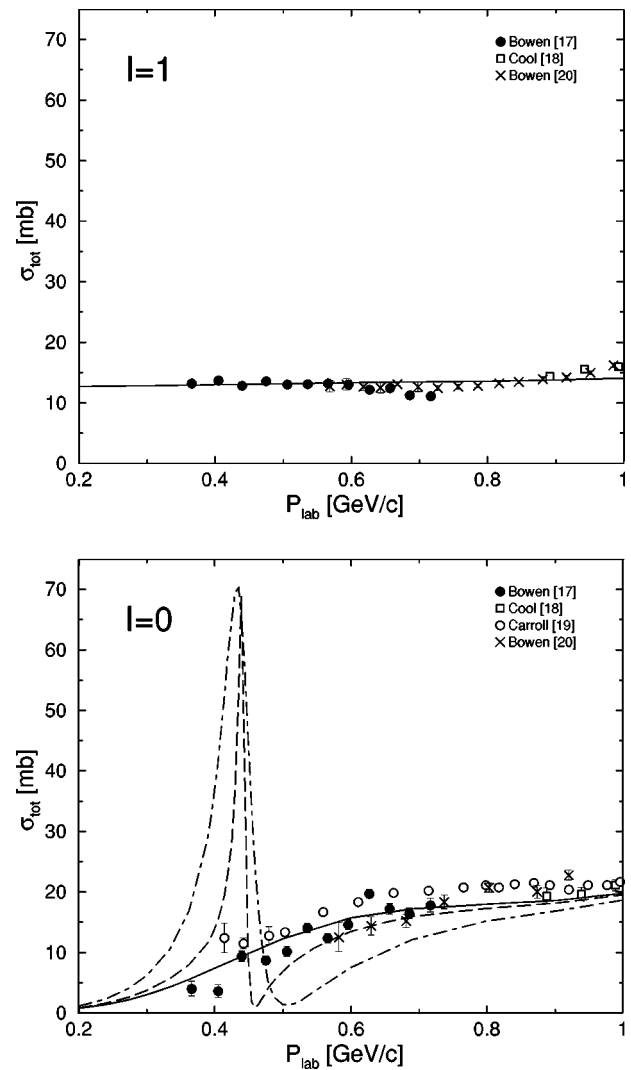


FIG. 2. KN elastic cross section in the isospin channels $I=0, 1$. The solid line is the result of the original Jülich model I from Ref. [11]. The dashed (dash-dotted) line shows results where a Z^+ resonance with a dynamically generated width of 5 (20) MeV is included. Experimental data are taken from Ref. [17] (filled circles), Ref. [18] (open squares), Ref. [19] (open circles), and Ref. [20] (crosses).

the Z^+ . The cutoff mass occurring in the vertex form factor, cf. Eq. (2.23) of Ref. [16], was fixed to 2 GeV. The bare masses used are 1545 MeV (for the model with the width of 5 MeV) and 1558 MeV (for the width of 20 MeV), respectively.

The elastic cross sections (for the isospin channels $I=0, 1$) predicted by the two models with a Z^+ are shown in Fig. 2 together with the results of the original Jülich model I and the available experimental information [17–20]. The $I=1$ channel is shown here only to demonstrate the quality of the Jülich model. The Z^+ is, of course, assumed to be a $I=0$ resonance and therefore it does not change the results in the $I=1$ channel.

The Jülich model provides also a decent description of the data in the $I=0$ channel. Its prediction might lie slightly too low at higher energies, however, one has to take into account

that the data also scatter somewhat. In any case, it is obvious that the deviation of the Jülich model and also the variations between the different datasets are by no means comparable to the impact of the Z^+ on the $KN(I=0)$ cross section. It is also clear that the Z^+ as predicted by Ref. [6] and as supposedly seen in the experiments [1–5] lies well within the energy range covered by KN data. Indeed, there are even data points from two independent experiments [17,19].

There is no way to reconcile the present $KN(I=0)$ cross section data with the existence of a $Z^+(1540)$ with a width of 5 MeV or more. In view of the curves shown in Fig. 2 it is clear why Arndt and Collaborators saw such a strong increase of the χ^2 in their partial wave analysis once the Z^+ (with $\Gamma=5$ MeV or more) was included [8]. One of their conclusions was that the Z^+ could have a width of order 1 MeV or less. We did not consider such a small width within our model. However, it is clear that reducing the width significantly would eventually lead to results that coincide with the ones of the Jülich model—besides an isolated narrow peak somewhere. Since there are no data below $p_{lab}=0.336$ GeV/c there is indeed also room for the Z^+ at energies much closer to the KN threshold. However, then one would need to find a dynamical explanation why the structure seen in the experiments [1–5] appears at a significantly higher KN invariant mass there—provided, of course, that it has something to do with the pentaquark state predicted in Ref. [6].

Results for the P_{01} phase shift are shown in Fig. 3. Note that the phases for the models with the Z^+ resonance pass through 90 deg around $p_{lab}=0.44$ GeV/c and then continue to rise beyond 180 deg. Therefore we show them here mod π so that they fit on the same graph and approach the Jülich model and the results of the phase shifts analyses again at higher energies. Also here it is clear that the existence of a Z^+ with a width of 5 MeV or more would lead to a tremendous change.

In summary, we have demonstrated the impact of a $Z^+(1540)$ with a width of 5 MeV or more on the $KN(I=0)$

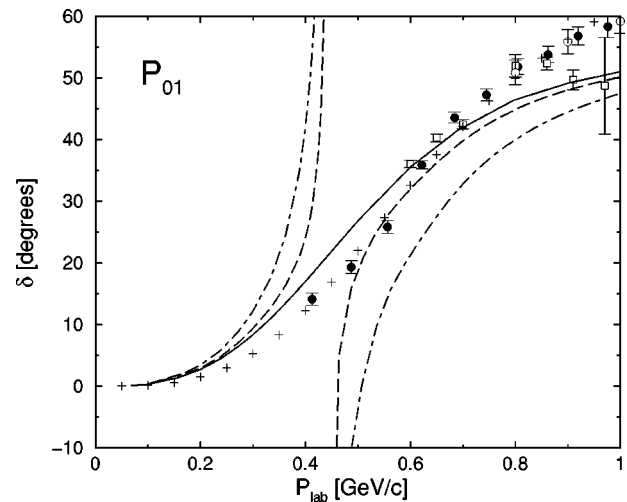


FIG. 3. KN phase shifts in the P_{01} partial wave. The solid line is the result of the original Jülich model I from Ref. [11]. The dashed (dash-dotted) line shows results where a Z^+ resonance with a dynamically generated width of 5 (20) MeV is included. Experimental phase shifts are taken from Ref. [21] (open circles), Ref. [22] (open squares), and Ref. [23] (filled circles and pluses).

elastic cross section and on the P_{01} phase shift. Even though the KN data in the relevant energy range show sizable uncertainties, it is evident that the rather strong enhancement of the cross section caused by the presence of a $Z^+(1540)$ would be in clear contradiction to the experiments. Only a much narrower $Z^+(1540)$ state could be reconciled with the existing empirical information on KN scattering [7,8]—or the predicted pentaquark state must occur at an energy much closer to the KN threshold. In any case it would be desirable to remeasure KN scattering around the energy of the suspected $Z^+(1540)$ resonance using the present day much more advanced accelerators and detector systems.

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