Time delayed K^+N reactions and exotic baryon resonances

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Abstract

Evidences and hints, both from the theoretical and experimental side, of exotic baryon resonances with $B = S$, have been with us for the last thirty years. The poor status of the general acceptance of these Z^* resonances is partly due to the prejudice against penta-quark baryons and partly due to the opinion that a proof of the existence of exotic states must be rigorous. This can refer to the quality and amount of data gathered, and also to the analytical methods applied in the study of these resonances. It seems then mandatory that all possibilities and aspects be exploited. We do that by analyzing the time delay in K^+N scattering, encountering clear signals of the exotic Z^* resonances close to the pole values found in partial wave analyses.

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1 Introduction

With the advent of the N^* program at Jefferson Lab [1] and the forthcoming Japan Hadron Facility [2], the interest in baryon resonances has increased over the last few years. Mysteries of veteran resonances, the hope to find new and 'missing' ones and the study of model predictions like the Unitarized Chiral Perturbation Theory [3] are only some topics worth mentioning in this context. But of course, one of the most interesting and exciting subject is the quest to find exotic hadrons [4]. Not all such hadronic states which we would call exotics, can be identified unambiguously. In the mesonic sector this would apply for glueballs, hybrids and mesonic molecules with conventional quantum number assignments. A sure candidate for an exotic meson would be the so-called J^{PC} exotic, which cannot be made up of quark anti-quark pair and appears with quantum numbers, $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}$ etc. Some candidates have indeed been found [5], but as in the case of exotic baryons they are not yet fully accepted. In the baryonic sector, a clear example of an exotic baryon would be one with its baryon number equal to the strangeness quantum number, i.e $B = S$. Indeed, such a hadronic state would either have to be a composite of five valence quarks, i.e., $q^4 \bar{s}$ with $q \neq s$, or a $K^+ N$ molecule i.e. a bound state of hadrons. These resonances are usually called Z or Z^* resonances. Evidence for the existence of such resonances dates back to the early 70' s (see [6, 7] for a collection of references on early KN experiments) and continues in the 80's (see the reference list in [8, 9]). This has been accompanied by theoretical predictions mostly in favour of the existence of penta-quarks [10, 11]. The situation is, however, more than confusing as the experimental signals are called 'pseudoresonances', 'doorways', 'resonance-like structures' and 'resonance-like loops' (moving counterclockwise in the Argand diagrams). These terms do not carry much physical meaning. We say this because, a resonance is at least theoretically, clearly defined as an unstable state characterized by different quantum numbers. The physical reasons for this caution are also not always clearly stated in the papers. However, in [12] we find the following statement: "Martin and Oades [2] [our reference [13]] interpreted these waves as complicated structures in the unphysical sheet instead of simple resonance poles, because the peaks of the speed plots did not coincide with the peaks of the "resonance". This is also the case for the three waves obtained in the present paper." Since we have already done an analysis of time delay (a concept related to speed plots as we shall explain below) [14, 15, 16], the above statement has motivated us to look into the matter more closely. Using the latest $K^+ N$ scattering data in the form of phase shifts and T-matrix solutions [8, 17], we calculate both the time delay and speed plots. We adopt the conservative point of view that we can promote eventually a resonance candidate to a fully accepted member of the resonance spectrum, only if the pole values of the masses found in the partial wave analysis agree with the values of peaks in speed plots and time delay. This restriction is more than one can impose on standard resonances. For example, the S_{11} resonance $N(1535)$ which is claimed to

be missing in the speed plots [18] and the P_{31} resonance $\Delta(1910)$ which gives no signal in the time delay plots [14, 15] are both taken as well-established resonances. Hence, our requirement for the confirmation of an exotic Z^* resonance is doubly strict.

2   Time delay and speed plots

In this section, we shall discuss the concepts of time delay and speed plots. Though both the methods are useful tools in analyzing resonances, they are different quantities (in certain cases, they differ only by a crucial minus sign) and their origin is also different. Time delay has an intuitive background which we would like to explain. The authors of [19] in a section where they compare Feynman diagrams to electric circuits state: "If it is possible for the intermediate particle to be *real*, then the process becomes unbounded in space-time and the corresponding amplitude singular". If this intermediate state (formed for example in two body scattering) is in the *s*-channel and is also a resonance, the singular amplitude can be tamed by a Breit-Wigner form, at least for elementary processes like for example the $e^+ e^- \rightarrow Z^0 \rightarrow \mu^+ \mu^-$ reaction. A similar 'catastrophe' can take place with a particle in the *t*-channel if one starts with an unstable particle [20], but this happens because we have violated the requirement that the scattering states be asymptotically free at large distances from the scattering centre. In any case, both reactions are non-localized ('unbounded') in space-time. The first case which is of interest for us here, can be visualized as follows: a resonance is produced on-shell at a space-time point (t_1, x_1), it propagates for some time and decays at a space-time point (t_2, x_2). Certainly, the reaction is time delayed (by an amount $\Delta t = t_2 - t_1$) and the time delay has to be *positive*. This picture is qualitatively model independent, as it does not depend on the form of the analytical tool by which the resonance is described (Breit-Wigner, a modified version of the same, etc.) and this makes it useful for broad hadronic states. Eisenbud and Wigner [21, 22, 23] found a way to evaluate this time delay, Δt, from the phase shift δ as,

$$\Delta t = 2\hbar \frac{d\delta}{dE} \,. \tag{1}$$

It can also be evaluated from the S matrix, generalizing at the same time, the time delay in elastic channels (1) to an arbitrary reaction $i \rightarrow j$ as, [24]

$$\Delta t_{ij} = \Re e\left[-i\hbar (S_{ij})^{-1} \frac{dS_{ij}}{dE}\right] \tag{2}$$

with the identification, $\Delta t_{ii} = \Delta t$. Defining the T matrix as

$$S_{kj} = \delta_{kj} + 2iT_{kj} \,, \tag{3}$$

with

$$T_{kj} = \Re e T_{kj} + i\Im m T_{kj} \tag{4}$$

we get

$$S_{ii}^* S_{ii} \, \Delta t_{ii} = 2\hbar \left[\frac{d\Re e T_{ii}}{dE} + 2\Re e T_{ii} \frac{d\Im m T_{ii}}{dE} - 2\Im m T_{ii} \frac{d\Re e T_{ii}}{dE} \right]. \tag{5}$$

Parameterizing a general T-matrix for the elastic channel in the presence of non-zero inelasticities, through the phase shift δ and the energy dependent inelasticity parameter η as,

$$T = \frac{\eta e^{2i\delta} - 1}{2i}, \quad 0 < \eta \le 1 \tag{6}$$

one can show that Δt is given by (1) even if $\eta \ne 1$. Time delay can be positive as well as negative. A big positive peak is expected within the kinematical vicinity of a resonance. Large regions of negative time delay can occur due to the opening of new channels or due to a repulsive interaction, or in the presence of several resonances even with all inelasticities zero [25]. Sometimes one hears/reads statements like 'the phase shift has to change sharply to indicate a resonance' or 'a phase motion indicates a resonance'. Very often it is stated that the phase shift has to increase by an odd multiple of $\pi/2$ while passing through the resonance region. Whereas the first statement is not precise enough, the second one is model dependent. Indeed, it originates from

$$\delta_{res}(E) \simeq \tan^{-1} \left[\frac{\Gamma/2}{E_R - E} \right] \tag{7}$$

which gives a Breit-Wigner form, namely,

$$\frac{d\delta}{dE} = \frac{\Gamma}{2} \frac{1}{(E_R - E)^2 + \Gamma^2/4} \, . \tag{8}$$

The reason behind both the above statements is actually the time delay, which is a model independent analytical justification of both of them. Moreover, as evident from the last equation, $\Delta t(E)$ is essentially the spectral density used to calculate survival probabilities [26] which carries some importance if Δt is not a Breit-Wigner.

The concept of time delay and its connection to resonances is well documented in many papers and found its entry in many textbooks. For a complete list of references we refer the reader to [16]. Here we remark that an operator for time delay has been found by Lippmann in [27]. Time delay can also be applied to steady-state solutions of Maxwell equations for the total reflection case [28], to chaotic scattering [29] and to transport theory in heavy ion collision [30], all showing the wide applicability of Δt. Before applying it to KN scattering, we would like to compare it with speed plots.

The speed plot is defined through

$$SP(E) = \left| \frac{dT}{dE} \right|. \tag{9}$$

Its first appearance is less clear than in the case of time delay. It probably stems from the Argand diagrams, as it describes the speed at which the curve in the Argand

diagram is traversed with E playing the role of the affine parameter. Using equation (6) we get,

$$SP(E) = \sqrt{\eta^2 \left(\frac{d\delta}{dE}\right)^2 + \frac{1}{4}\left(\frac{d\eta}{dE}\right)^2} \tag{10}$$

which shows that if $\eta = 1$, $SP(E) = |\Delta t|/2$. Even in this case, a speed plot is not the same as a time delay plot, since large negative regions in the time delay plots will become positive peaks in the speed plots. This fact is unfortunate, since only positive peaks in time delay indicate a resonance. For example, the negative dips in time delay in the S_{01}, D_{03} and D_{15} partial waves in Fig. 2, appear as positive bumps in the speed plots. In the P_{01} and P_{13} partial waves, one can see that the resonant peak in the speed plot is broadened as compared to the time delay peak which is narrower due to the presence of negative time delay. That time delay can be negative even in the case of $\eta = 1$ was noticed already by Wigner [21] and an explicit example of this is given in [25]. If $\eta \neq 1$, the situation described above still persists, but then, even the proportionality, $SP(E) = |\Delta t|/2$ vanishes. Indeed, we could have done our analysis without using the speed plots. However, since two earlier references used it in analyzing the KN data, we would like to make a correct comparison with their results.

3 Time delay, speed plots and resonances in K^+N scattering

Since the T-matrix (see Fig. 1) solutions found in [8], agree very well in the crucial cases with the single energy values of the T-matrix and phase shifts, we calculate, with the exception of the S_{01} partial wave (where we also use the single energy values), the time delay and speed plots from these solutions. The results for time delay are presented in Fig. 1 and for the speed plots in Fig. 2, where for comparison we have included the time delay results too. It appeared to us that in the case of the partial wave, S_{01}, the agreement between the solution and single energy values is not as good as in the other partial waves. We therefore decided to calculate Δt from the solution as well as from a fit made to the data points. These results can be found in Fig. 3.

The T-matrix poles found in [8] are: $P_{01}(1831)$, $P_{13}(1811)$, $D_{03}(1788)$ and $D_{15}(2074)$. Comparing these values with the peak positions in the time delay plots for the corresponding partial waves, we see that the agreement is very good. We do not expect a complete agreement here between pole values and time delay peak values as this also does not occur in the conventional cases of pion-nucleon resonances [14, 15]. As evident from the theoretical example in [25], the mass parameters appear shifted in time delay plots due to overlapping effects of several resonances. The agreement of the peak values in the speed plot with the above mentioned pole values is also excellent. Hence we can ask ourselves the question: 'what other objection prevents us from accepting the four Z^* exotic resonances'? Note that the pole values
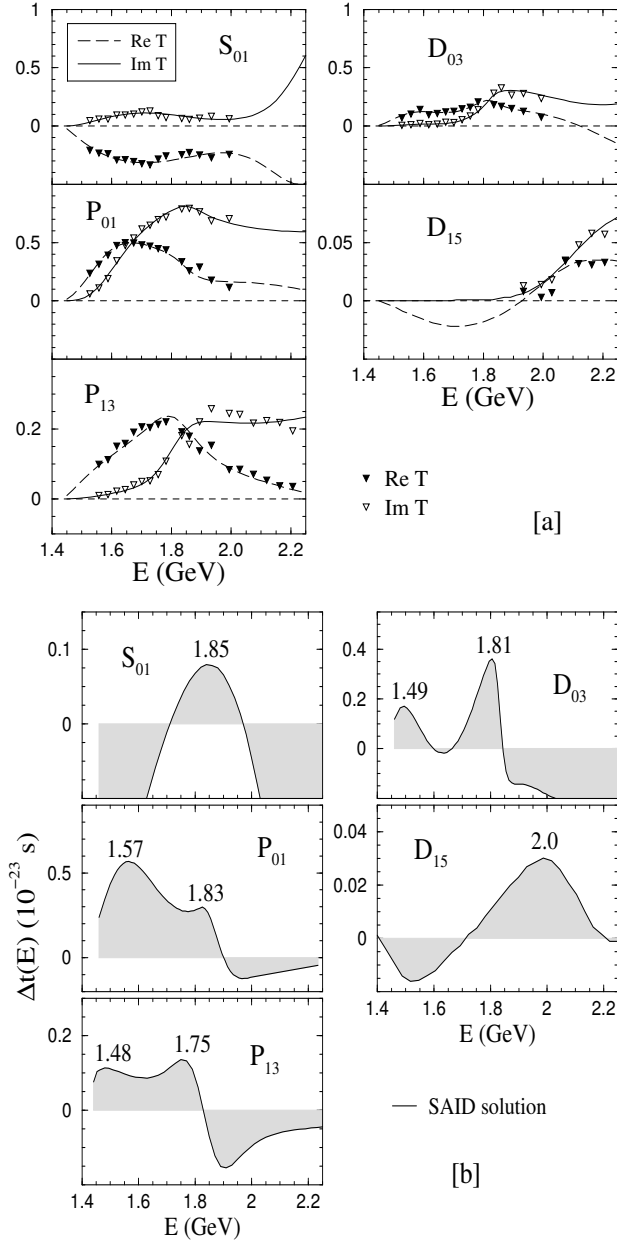
Figure 1: (a) Real (dashed lines) and imaginary (solid lines) parts of the T-matrix solutions [8] as compared to the single energy values the real part (filled triangles) and imaginary part (open triangles) for various partial waves in K^+N scattering (b) time delay evaluated using the T-matrix solutions (shown in (a))
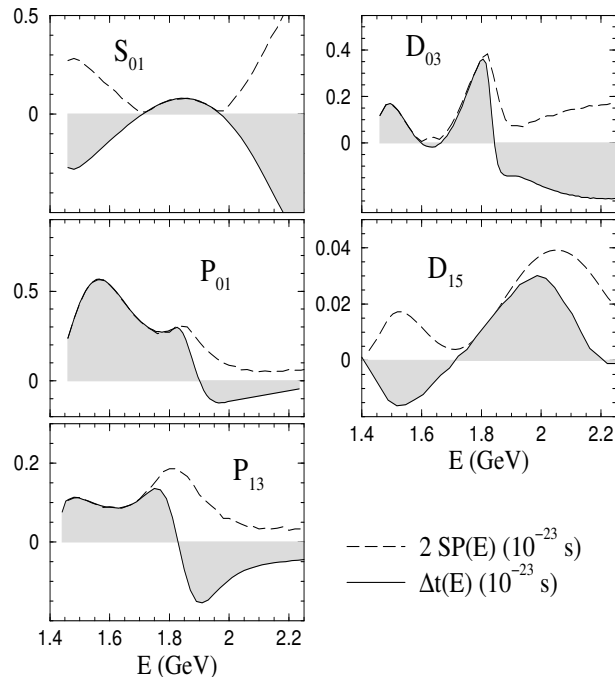
Figure 2: Comparison of time delay and speed plots in various partial waves of K^+N scattering.

(and of course the corresponding peaks in our plots) for P_{01}, P_{13} and D_{03} display a certain regularity. The three pole values are very close to the $K^*(892)N$ threshold. This is, however, a well known phenomenon. For instance, there are several well established pion-nucleon resonances close to the ρN threshold. Theoretically, this phenomenon has been known since the early 60's [32]. In [31] (mentioned also in [9]) it is speculated that the signals for the resonances could be faked by a K^*-box diagram (essentially the pion exchange diagrams $KN \rightarrow K^*N$ and $K^*N \rightarrow KN$ glued together). In principle, we could address a similar question for higher lying pion-nucleon resonances by replacing the K^*-box with a ρ-box, i.e. replacing the K by π and K^* by ρ.

Furthermore, in [33] the very same K^*-box was used as an *input* to dynamically generate the Z^* resonances. The predicted Z^* resonances in [33] are S_{01} and D_{03} *around* 1830 MeV. The model in [33] has been put to a partial test in [6] which analyzes data by using this model. The speed plots in [6] agree very well with our results. This actually means that, had the authors of [6] evaluated time delay, their results would have also agreed with ours. It is important to note that our results for the time delay indicate that the signal for a particular Z^* resonance is a genuine one. To understand this, we have to go back to the pion-nucleon resonances [14]. In [14] it was found that the opening of a new channel drives the positive time delay in the elastic channel into regions of negative time delay. It actually starts
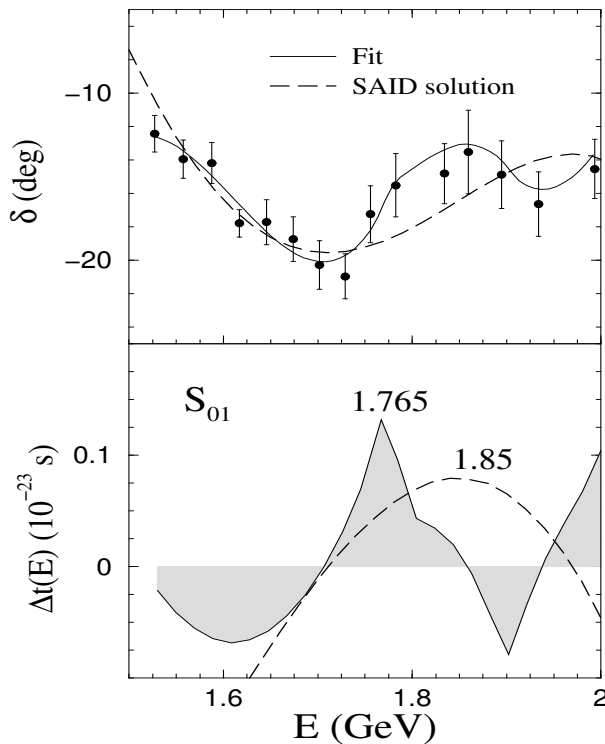
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Figure 3: Single energy values of phase shifts (filled circles) and time delay evaluated from a fit (solid line) to these phase shifts and from the solution (dashed line) as in Fig. 1, for the S_{01} partial wave in K^+N scattering.

becoming negative around the threshold of a new channel, very often interfering with the positive signal of the resonance itself. It was found that in more than one case, this leaves only a small positive peak (due to the resonance). That this is bound to happen is also clear from the connection of time delay with density of states (see the discussion in [14] and [16]). A 'removal' of the initial states due to inelasticity makes the time delay negative. The probability of this inelastic channel usually decreases with energy. Hence, in the *absence* of a resonance, for the K^*-box diagram, we would expect only a negative time delay around $K^*(892)N$ threshold becoming a positive *continuum* (due to the off-shell box diagram) at much higher energies. We do not find such a behaviour in our time delay analysis, but rather positive peaks around 1830 MeV, followed by regions of negative time delay. This is identical to the case of standard resonances in pion-nucleon scattering. Note that this conclusion would be impossible to make using solely speed plots.

As mentioned in the Introduction, the rigor that one wishes to apply to exotics, demands that pole values be equal to the peak values of time delay and speed plots; a consistency not always encountered in the standard hadron resonances. Hence, we shall only briefly discuss the other peaks found in our plots. The peak in S_{01} at

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1850 MeV (or 1765 MeV in Fig. 3) was interpreted in [33, 6] as a resonance. In [11] a resonance at (1710) MeV in the S_{01} partial wave was predicted. The time delay peaks at 1.5 GeV, in the P_{01}, P_{13} and D_{03} partial waves, also have a certain regularity. Some recent calculations [34] made within the collective quantization scheme for chiral solitons predict a penta-quark state, essentially an exotic Z^* around mass 1570 MeV. In yet another chiral soliton model [35], a Z^* at 1530 MeV was predicted. In ref. [36], the authors show that the $pp \to n\Sigma^+ K^+$ reaction provides optimal conditions to detect the Z^* if its mass is located around 1.5 GeV. Finally, we also note that in a much older analysis [12], one can see a clear peak around 1550 MeV in the speed plots of Fig. 3, although the authors do not explicitly mention this fact in their table of resonance parameters. These predictions taken along with our findings of the low energy peaks in time delay could possibly hint towards the existence of a low mass Z^* in addition to the one around 1850 MeV.

4   Conclusions

The last entry of the Z^* exotic resonances into the Particle Data Group compilation was in 1992 [37]. In the same edition, it was remarked that it might take twenty years before the issue of the existence of the Z^* resonances is settled. One might think that this is due to the lack of data. However, this is not the case. The first data sets, date back from 1969/1970, followed by several others in the 70's and 80's with the last one in 1982. The latest analysis is not restricted to a single data set, but includes many of them [8]. Hence we cannot blame the lack of data if we are reluctant to decide the fate of the Z^*'s.

In [12] it was remarked that: "It was found that both data showed reasonable agreement with each other but the agreement with the published analyses were not satisfactory." Reference [12] is the same which does not find an agreement between pole value and values found in speed plots (similar to [13]). Hence an internal consistency of data and analysis is required. As far as the existence of resonances is concerned, this can be done e.g. by checking if the pole values agree with values obtained from time delay method and speed plots. We emphasize here the time delay method since in contrast to speed plots the resonance region in the time delay plots has to be positive *. As remarked in the Introduction, this is more than we have for some of the four-star pion-nucleon resonances. Our analysis reveals that the pole values found in [8] are in excellent agreement with the values for the masses found in time delay and speed plots.

From a collection of data set progressing in time one would expect certain improvements, here with regard to resonance extraction. In one of the early analysis

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*In principle, it could have happened that we find a peak in the speed plots very close to the pole value. However, if in the time delay plot, it turns out that this peak is negative, we cannot attribute it to a resonance.

of KN scattering, it was demonstrated that 'polarization measurements would be very helpful in demonstrating the existence of these resonances'. At that time, only one polarization measurement existed. However, this suggestion was picked up later in a series of experiments (see [8] for a list of references) and included in the analysis in [8].

Finally, from different data and different analyses, one would demand a certain consistency among each other [†]. Here comes a small surprise. Reference [6] analyzed the early data from 1970's using at the same time a theoretical input to distinguish between solutions. This input is the model in reference [33] discussed in the previous section. Fig. 3 in [6] displays the speed plots for S_{01}, P_{01} and D_{03} partial waves in KN collisions calculated in 1973. Their form resembles very much our results for speed plots depicted in Fig. 2. More importantly, the peak values of the speed plots in [6] are in excellent agreement with ours, though our result is based on a bigger data set and as far as we can say with lesser theoretical input. Yet another surprise comes, when we realize that the speed plot peaks in the P_{13} and D_{03} partial waves in [12] are around 1825 MeV.

To summarize, we can say that, we laid certain restrictions for the existence of the exotic Z^* resonances. Within these restrictions the results were found to be consistent, hinting towards the existence of these resonances. We think that these hints should be taken seriously.

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Note added after publication: After this work was published, we became aware of the work by T. Nakano *et al.* (Phys. Rev. Lett. 91 (2003) 012002) where excellent experimental evidence for a penta-quark state with mass around 1.54 GeV was reported. We speculate that it can be identified with the $P_{01}(1.57)$ of the present work.

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