Evidence of Pentaquark States from $K^+N$
Scattering Data?

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Abstract

Motivated by the recent experimental evidence of the exotic $B = S = +1$ baryonic state $\Theta$ (1540), we examine the older existing data on $K^+N$ elastic scattering through the time delay method. We find positive peaks in time delay around 1.545 and 1.6 GeV in the $D_{03}$ and $P_{01}$ partial waves of $K^+N$ scattering respectively, in agreement with experiments. We also find an indication of the $J = 3/2$ $\Theta^*$ spin-orbit partner to the $\Theta$, in the $P_{03}$ partial wave at 1.6 GeV. We discuss the pros and contras of these findings in support of the interpretation of these peaks as possible exotics.

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In a recent letter by Nakano et al. [1], strong experimental evidence for the exotic state, characterized by the quantum numbers $B = S = +1$, with a mass and width of $1.54 \pm 0.01$ and $0.025$ GeV respectively, was reported. This could be interpreted as a molecular meson-baryon resonance (see e.g. [2]) or a pentaquark baryon [3, 4, 5], hence its importance. It was actually since the late sixties that such a state was predicted [6]. Some other groups [7] also reported similar results which shifts the evidence for the new state from plausibility to certainty. In this note, we would like to shed some light on these findings by examining whether this exotic state around 1.54 GeV is actually supported by phase shifts [8] obtained from older data on kaon-nucleon elastic scattering. If our analysis is taken in support of the experimental interpretation, we can assign or speculate about the $L_{2I,2J}$ quantum numbers. Indeed, according to our analysis, the exotic state found in [1] and [7] is likely to be either a $P_{01}$ (this would be in agreement with the prediction made in [9] which actually prompted the experiments) or $D_{03}$ (or maybe even $P_{03}$).
In [10], we used the time delay method of Eisenbud, Wigner [11] and Smith [12] (see also [13, 14, 15]) to detect resonances from the phase shift derivative. The peak in the time delay given by,

$$\Delta t(E) = 2\hbar \frac{d\delta_l(E)}{dE}$$  \hspace{1cm} (1)

where $\delta_l$ is the phase shift in the $l^{th}$ partial wave, corresponds to the resonance position $E = E_R$. In [10], we found that this method yields an excellent agreement with the established meson resonances. We noticed that the time delay method, which is the quantification of phase shift motion (in the extreme one says that the phase shift makes a 180° jump passing through 90°), is very sensitive to ‘small structures’ in data, which might be overlooked otherwise.

The time delay in scattering can also be expressed in terms of the transition matrix as [10],

$$S_{ij}^* S_{ij} \Delta t_{ij} = 2\hbar \left[ \Re \left( \frac{dT_{ij}}{dE} \right) + 2 \Re T_{ij} \Im \left( \frac{dT_{ij}}{dE} \right) - 2 \Im T_{ij} \Re \left( \frac{dT_{ij}}{dE} \right) \right]$$  \hspace{1cm} (2)

where $i$ and $j$ represent the incident and outgoing channels in a scattering process. In [16], we applied the time delay method to find resonances in $K^+N$ elastic scattering, using the above relation and model dependent $T$-matrix solutions [8]. We found evidence for low-lying $K^+N$ resonances around 1.5 GeV in the $P_{01}(1.577)$, $P_{13}(1.48)$ and $D_{03}(1.49)$ partial waves. It is important to note that analyses of the $K^+N$ elastic scattering data using other methods such as poles or argand diagrams have not found resonances around 1.5 GeV.

In the present work we do not use the model dependent solutions of the $T$-matrix along with eq. (2), but rather the single energy values of phase shifts to evaluate time delay using eq. (1). We use these phase shifts to reduce the model dependence in our calculations and compare our results obtained from the older data with the recent experimental findings.

Before going into details of the analysis of the exotic case, let us see how the method of time delay works in the case of established $N^*$ resonances. This is done in Fig. 1, for the standard $(B = 1, S = 0)$ $D_{13}$ resonance. We see a prominent peak of the four-star $D_{13}(1520)$, but also smaller peaks for the three-star $D_{13}(1700)$ and the less established two-star $D_{13}(2080)$ resonances. The smaller peaks are due to the small phase shift motion which we took into
account by making a polynomial fit to the single energy values, rather than using the energy dependent $T$-matrix solutions. Though in principle, such a fit is not always the best way of analysing data, it is justified here by the fact that (i) even small phase shift motion seems to agree with established resonances and (ii) we think that a $\chi^2$ fit would give the same results given the very small error bars (i.e. even the smaller peaks will not vanish) (iii) in [16] we evaluated time delay using smooth model dependent solutions of the $T$-matrix and obtained very similar results (iv) in [10] we applied the same method of fitting single energy values and confirmed all existing meson resonances (well established and less established) (v) last but not least the peak values found in the present work are very close to those found by recent experiments. It is also interesting to note that a peak in the speed plots was found at 1540 MeV in the $P_{01}$ partial wave in an old $K^+N$ scattering experiment [17]. Note also that calculating the time delay from single energy values of phase shift is less model dependent than the model dependent solutions.

Motivated by the recent evidences [1, 7], we decided to evaluate the time
Figure 2: (a) Single energy values of phase shifts (filled circles), model dependent solutions (dashed line) [3] and fit (solid line) (b) time delay in $K^+N$ elastic scattering evaluated from the fit to the phase shift (solid line).

Figure 3: Same as Fig. 2
delay (as in eq. (1)) using the available $K^+N$ scattering phase shifts and check for small structures which could give rise to time delay peaks. In [16], the calculations were done using eq. (2) and smooth model dependent $T$-matrix solutions which could have possibly missed or shifted some peaks. As in the standard baryon case, here too we see small structures in phase shift which give rise to time delay peaks. We see in Fig. 2, in the $D_{03}$ partial wave, a peak at $1.545$ GeV, followed by other higher lying resonances. In [16] this corresponds to the value of $1.49$ GeV. In Fig. 3 (the $P_{01}$ partial wave), we find the lowest resonance at $1.6$ GeV which corresponds in [16] to a peak at $1.57$ GeV. Note that in hadronic resonances, the resonance parameters quoted by different groups, often differ from each other (by some $10-20\%$) depending on the experiment and method used [18]. We therefore conclude that the values we found here and in [16], are in good agreement with the recent experiments [1, 7].

It was recently pointed out [19] that if the $\Theta (1540)$ is $udud\bar{s}$ with $J^p = 1/2^+$, then the correlations among QCD forces necessarily imply the existence of $\Theta^*$ with $J^p = 3/2^+$ which is probably only slightly more massive than the $\Theta$ (the mass difference between $\Theta$ and $\Theta^*$ would be decided by the strength of the spin-orbit forces within this exotic). The spin-orbit partner with $J = 3/2$ is also predicted within a chiral constituent quark model in [5], in contrast
to the soliton model which rules out the existence of such a partner. This possible $\Theta^*$ is expected to be broad [20]. In view of these predictions, we found it important to analyse the time delay in the $P_{03}$ partial wave where a possible $J = 3/2$ partner of the resonance at 1.6 GeV in the $P_{01} (J = 1/2)$ partial wave could exist. The $J = 1/2$ partner of the $D_{03}$ resonance at 1.545 GeV (Fig. 2) would correspond to the $D_{01} (J = 1/2)$ partial wave, the data on which does not exist in the case of $K^+N$ elastic scattering (since $S = 1/2$ for the $K^+N$ system, $L = 2$ allows only $J = 3/2, 5/2$). In Fig. 4 we show the time delay analysis for $P_{03}$ and indeed find similar peaks (around 1.6 and 1.8 GeV) as in the $P_{01}$ case. However, since the error bars on the phase shifts in the $P_{03}$ case are large, this finding of the $J = 3/2$ partner should be treated with caution. Note also that the model solution (dashed line) for phase shift would not give rise to any resonant structure. We do think, however, that such an agreement between peak positions in the $P_{01}$ and $P_{03}$ partial waves cannot be a coincidence and the spin-orbit partner will most likely be confirmed when better data on $K^+N$ elastic scattering becomes available.

The widths of the resonances found in our analysis using time delay seem to be somewhat larger than those predicted by the recent experiments [1, 7]. However, two of these experiments have been done on nuclei, using carbon and xenon, which could lead to a reduction of the resonance width as compared to that in free space. The width inside nuclear medium could reduce due to (a) modification of the pentaquark-kaon-nucleon vertex inside the medium and (b) interaction of the decay products with the nucleus, which involves Pauli blocking of nucleon states as well as modification of the $K^+$ propagator. Studies of similar effects in other resonances [21], have indeed shown the nuclear effects to be important.

The above interpretation could however have a caveat worth discussing. One would not expect any inelasticities to be present in the the relevant 1.5 GeV region due to its being close to the $KN$ threshold. Hence, as obvious from Fig. 1 for the prominent $D_{13}$ resonance, the phase shift is expected to jump by $\pi$. This does not happen in Figs 2-4. The reason behind it could be twofold. Either the positive time delay peak in the 1.5 GeV region does not signify a proper resonance, or as explained below, a strong non-resonant background exists in this region. The first possibility casts strong doubts on interpreting the experimentally found bump in the cross section as a proper resonance simply because the phase shifts in any of the partial waves in the
same energy region fail to make a ‘π-jump’. Indeed, not every peak in the cross section is necessarily a resonance [22]. Such an interpretation would be in favour of the fact that no pole values have been found in the 1.5 GeV region through partial wave analysis and also in agreement with the conclusion in [23]. The second possibility of a non-resonant background cannot be excluded a priori. Already in potential scattering, the total phase shift is a sum of the resonant and non-resonant part. The latter is usually written as $\tan^{-1}[j_l(ka)/n_l(ka)]$ where $k$ is the momentum, $a$ the potential range and $j_l, n_l$ are linear combinations of spherical Hankel functions [24]. Certainly, the aforementioned ‘π-jump’ occurs only completely if the non-resonant part is missing. To avoid the reference to potential scattering one might also parametrize the $S$ matrix with the inclusion of the energy dependent background phase $\eta_i$ [25] as

$$S = e^{2i\eta_i} \left[ 1 - 2i \frac{E_R \Gamma_i(E)}{E^2 - E_R^2 + iE_R \Gamma(E)} \right]$$ (3)

which again leads to a distortion of the phase shift and hence time delay too. If we accept the peak around 1.5 GeV in the cross section and the time delay as a proper resonance, there seems to be no way out as to accept also a strong non-resonant background. To decide which one of the two possibilities is the most likely one, we give two physical examples of phase shifts in strong interaction. The $P_{1/2}$ phase shift in $p-\alpha$ elastic scattering jumps from 0° to about 60° giving the first excited $^5Li$ state which lies much below the first inelastic threshold, namely the $p + \alpha \rightarrow d + ^3He$ reaction [26]. Another example is that of the $P_{1/2}$ level of $^5He$ found in elastic $n-\alpha$ scattering where again the phase shift jumps only by about 40° [27]. In both cases the phase shifts are neither steep nor do they perform the ‘π-jump’ due to the presence of hard sphere potential scattering (non-resonant background in other words). Note however that the above resonances are well established.

The experimental papers do not give the $L_{2I,2J}$ assignments of the resonance around 1.5 GeV. If we attribute the form of the phase shift due to a resonant and background part, we can speculate from our time delay plots (Figs 2-4) and our earlier work [16], that this resonance could either be $D_{03}$, $P_{01}$ or $P_{03}$. As mentioned in [9], we would also like to note that the older $K^+N$ scattering data is available from around 1.525 GeV onwards centre of mass energy of the $KN$ system. This could be the possible reason as to why the low-lying exotic was not spotted by others in the past. However, the time
delay method clearly displays the peaks in the $D_{03}$ and $P_{01}$ partial waves at 1.545 and 1.6 GeV respectively. Though not with very reliable data, we do find peaks in the $P_{03}$ partial wave which could be the $J = 3/2$ partners of the ones in $P_{01}$.

Given the success of the time delay method using phase shifts [10], and the fact that we do find the recently reported exotic resonance around 1.5 GeV, we think that the higher lying resonances in our time delay plots should also be taken seriously. More so as the argument concerning the small inelasticity at threshold is not valid anymore. It would be useful to improve the statistics of the present experiments [1, 7] in the energy region of 1.8 GeV, to confirm the higher exotic states.

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References

[1] T. Nakano et al., Phys. Rev. Lett. 91, 012002 (2003).

[2] T. Barnes and E. S. Swanson, Phys. Rev. C 49, 1166 (1994).

[3] Robert L. Jaffe and Frank Wilczek, Preprint: MIT-CTP-3401, Jul 2003, e-Print Archive: hep-ph/0307341; Robert L. Jaffe, Phys. Rev. D 15, 281 (1977).

[4] S.I. Nam, A. Hosaka, H.C. Kim, Phys. Lett. B579, 43 (2004), Preprint PNU-NTG-06-2003, hep-ph/0308313; C. E. Carlson, C. D. Carone, Herry J. Kwee, Vahagn Nazaryan, Phys. Lett. B573, 101 (2003), hep-ph/0307396; ibid Phys. Lett. B579, 52 (2004), hep-ph/0310038. B. G. Wybourne, Aust. J. Phys. 31, 117 (1978); ibid, hep-ph/0307170; F. J. Llanes-Estrada, hep-ph/0311235; Hai-Yan Gao and Bo-Qiang Ma, Mod. Phys. Lett. A 14, 2313 (1999); D. Akers, hep-ph/0403142.

[5] L. Ya. Glozman, Phys. Lett. B575, 18 (2003); hep-ph/0308232.
[6] D. P. Roy and M. Suzuki, Phys. Lett. B 28, 558 (1969); D. P. Roy, J. Phys. G30, R113 (2004); hep-ph/0311207.

[7] S. Stepanyan et al., Phys. Rev. Lett. 91, 252001 (2003); V. Kubarovsky et al., Phys. Rev. Lett. 92, 032001 (2004) Erratum-ibid. 92, 049902 (2004); V. V. Barmin et al., Phys. Atom. Nucl. 66, 1715 (2003), Yad. Fiz. 66, 1763 (2003), hep-ex/0304040; J. Barth et al., Phys. Lett. B572, 127 (2003); A. E. Asratyan, A. G. Dolgolenko and M. A. Kubantsev, hep-ex/0309042; A. Airapetian et al., Phys. Lett. B 585, 213 (2004); A. Aleev et al., hep-ex/0401024; S. V. Chekanov et al., hep-ex/0404007.

[8] J. S. Hyslop, R. A. Arndt, L. D. Roper and R. L. Workman, Phys. Rev. D46, 961 (1992); phase shifts can be obtained from the SAID program made available on internet (URL: http://gwdac.phys.gwu.edu) by R. A. Arndt et al. To access it by telnet, link to gwdac.phys.gwu.edu with ‘LOGIN:said’. Password is not required.

[9] D. Diakonov, V. Petrov and M. Polyakov, Z. Phys. A 359, 305 (1997). Another prediction of a low-lying exotic with a mass around 1.57 GeV, can be found in H. Weigel, AIP Conf. Proc. 549, 271 (2002).

[10] N. G. Kelkar, M. Nowakowski and K. P. Khemchandani, Nucl. Phys. A 724, 357 (2003); hep-ph/0307184; N. G. Kelkar, M. Nowakowski, K. P. Khemchandani and S. R. Jain, Nucl. Phys. A 730, 121 (2004), hep-ph/0208197; N. G. Kelkar, J. Phys. G. 29, L1 (2003).

[11] E. P. Wigner and L. Eisenbud, Phys. Rev. 72, 29 (1947); E. P. Wigner, Phys. Rev. 98, 145 (1955).

[12] F. T. Smith, Phys. Rev. 118, 349 (1960); ibid Phys. Rev. 130 394 (1963).

[13] B. H. Bransden and R. Gordon Moorhouse, The Pion-Nucleon System (Princeton University Press, New Jersey, 1973). ; H. M. Nussenzweig, Causality and Dispersion Relations, Academic Press, New York and London 1972.

[14] A. Peres, Ann. Phys. (N.Y.) 37 179 (1966); J. M. Jauch and J. P. Marchand, Helv. Phys. Acta 40 217 (1967).
[15] J. Fraxedas and J. Sesma, Phys. Rev. C\textbf{37} 2016 (1988); J. R. Pelaez, Phys. Rev. D\textbf{55} 4193 (1997); P. Danielewicz and S. Pratt, Phys. Rev. C\textbf{53}, 249 (1996); S. Leupold, Nucl. Phys. A\textbf{695}, 377 (2001); C. David, C. Hartnack and J. Aichelin, Nucl. Phys. A\textbf{650}, 358 (1999); A. B. Larionov \textit{et al.}, nucl-th/0107031; N. G. Kelkar, J. Phys G: Nucl. Part. Phys. \textbf{29}, L1 (2003); hep-ph/0205188.

[16] N. G. Kelkar, M. Nowakowski and K. P. Khemchandani, J. Phys. G: Nucl. Part. Phys. \textbf{29}, 1001 (2003); hep-ph/0307134.

[17] K. Nakajima \textit{et al.}, Phys. Lett. \textbf{112B} 80 (1982).

[18] K. Hagiwara \textit{et al.}, (Particle Data Group), Phys. Rev. D \textbf{66}, 010001 (2002) (URL:http://pdg.lbl.gov).

[19] J. J. Dudek and F. E. Close, Phys. Lett. \textbf{B583}, 278 (2004); hep-ph/0311258.

[20] B. K. Jennings and Kim Maltman, hep-ph/0308286.

[21] M.J. Vicente Vacas and E. Oset, Preprint:FTUV-01-1214, IFIC-01-1214, Dec 2001, e-Print Archive: nucl-th/0112048; M. Hjorth-Jensen, H. Muther and A. Polls, Phys. Rev. C \textbf{50}, 501 (1994).

[22] H. C. Ohanian and C. G. Ginsburg, Am. J. Phys. \textbf{42} 310 (1974).

[23] J. Haidenbauer and G. Krein, “Influence of a Z+\textit{(1540)} resonance on K+N scattering”, hep-ph/0309243

[24] C. J. Joachain, \textit{Quantum Collision Theory}, North-Holland, Amsterdam 1975

[25] A. M. Badalian, L. P. Kok, M. L. Polikarpov and Yu. A. Simonov, Phys. Rep. \textbf{82}, 31 (1982); C. Garcia-Recio, J. Nieves, E. Ruiz Arriola and M. J. Vicente Vacas, Phys. Rev. D \textbf{67}, 076009 (2003).

[26] R. A. Arndt, L. D. Roper and R. L. Shotwell, Phys. Rev. C \textbf{3}, 2100 (1971).

[27] G. L. Morgan and R. L. Walter, Phys. Rev. \textbf{168} 1114 (1968).