On the search for a narrow penta-quark Z^+ baryon in NN interactions*

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The possibility for an observation of a narrow penta-quark Z^+ baryon in NN reactions is discussed. It is shown that the $pp \to n\Sigma^+K^+$ reaction at excess energies around 100 MeV above threshold provides optimal conditions for Z^+ baryon detection by an analysis of the nK^+ invariant mass spectrum, if the Z^+ mass is located around 1.5 GeV involving a rather narrow width.

The standard valence quark model builds up the low-lying baryons from three valence quarks qqq with strangeness from S=−3 to S=0, that are surrounded by a meson cloud or strong $q\bar{q}$ vacuum polarizations. However, also Fock states involving additional $q\bar{q}$ components are allowed which then can appear as baryonic resonances. The inverse life time of these excited states is proportional to the phase space for the decays allowed by quantum numbers. Interesting excitations are possible for a $qqqq\bar{q}$ configuration [1] which allows to construct S=+1 states denoted by Z baryons. The observation of Z baryons thus provides an unambiguous signal that the standard valence quark model has to be extended to a larger Fock space.

An experimental search for Z baryons was started in 1966 at the BNL [2] by the observation of a *clear* resonance peak in the K^+p and K^+d total cross section at kaon momenta around 0.9÷1.3 GeV/c. This novel baryonic resonance with strangeness S=+1, mass $M_Z \approx 1.91$ GeV and width $\Gamma_Z \approx 180$ MeV was interpreted as a SU(3) antidecuplet together with the $N^*_{11}(1480)$.

A review on the further experimental and theoretical activities and an evidence for strangeness S=+1 baryon resonances is given by the PDG in Ref. [3]. Summarizing 20 years of experimental activity on S=+1 baryons it is important to note that almost all searches were performed by KN elastic and inelastic scattering at kaon momenta corresponding to Z baryons in the mass range of $1.74 \le M_Z \le 2.16$ GeV. Furthermore, the resonance total widths reported in Ref. [4] are very large and range from 70 MeV to 845 MeV. Furthermore, an expectation for the heavy Z resonances is supported by the MIT bag model [1], where the lightest Z^+ baryon has a mass of 1.7 GeV and a smaller width.

On the other hand, in the large N_c limit of QCD baryons emerge as soliton configurations that have to be projected on proper quantum numbers. In this framework the exotic pentaquark Z^+ is the lightest member of the antidecuplet of baryons and arises naturally as a rotational excitation of the classical soliton (cf. Refs. [5]). For the most recent analysis of the Z^+ baryon properties we refer the reader to Refs. [6–8].

The theoretical predictions for the Z^+ mass (and width) in the soliton models vary in a wide range. Whereas the calculations in the Skyrme model of Ref. [6] predict a Z^+ mass of 1.7 GeV, the analysis within the framework of the chiral quark-soliton model [7] suggests a Z^+ mass around 1.5 GeV and quite narrow width $\Gamma_Z \le 15$ MeV due to specific contributions of soli-

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ton rotation (see for details Ref. [7]). The detailed analysis of the Z^+ width in the chiral quark soliton model indeed shows that the most favorable width should be about 5 MeV [9]. In this letter we will explore in particular if such a state might be detected in NN scattering. Furthermore, we point out that Ref. [8] predicts M_Z=1.58 GeV and a width Γ_Z=100±30 MeV. Thus the most recent calculations [7,8] suggest a low mass of the Z^+ baryon in a range that has not been investigated before experimentally [3,4].

Here we study the possibility of Z^+ (I=0, S=+1, $J^P=\frac{1}{2}^+$) observation in NN collisions, which can be performed at the COoler SYchlotron (COSY) in Jülich. Furthermore, we explore the effects due to a narrow Z^+ resonance [7] in the invariant mass spectra.

Since the Z^+ resonance couples only to the NK system it can be excited in real or virtual K^+n or K^0p scattering. Unfortunately, there are no data [10] available on the real K^+n scattering for momenta p_K<600 GeV/c, which correspond to the mass range $M_Z \leq 1.58$ GeV of our interest. On the other hand, data exist on the $K_Lp{\to}K_Sp$ reaction [11] that can be analyzed in order to evaluate the Z^+ baryon properties.

A virtual Z^+ excitation might be tested in $pp{\to}n\Sigma^+K^+$, $pp{\to}p\Sigma^+K^0$, $pn{\to}n\Lambda K^+$ and $pn{\to}p\Lambda K^0$ reactions through K-meson exchange. Furthermore, reactions with a neutron in the initial state basically are performed with a deuteron target which might not be suitable for a measurement of the Z^+ signal in the NK invariant mass; if the Z^+ is a narrow resonance, then an averaging over the deuteron spectral function might substantially distort the Z^+ signal. In principle this problem can be resolved by an additional measurement of the spectator nucleon of the deuteron and a full kinematical reconstruction of the final states. However, here we suggest to use the K^+ production channel, and also provide a motivation for the advantages of the $pp{\to}n\Sigma^+K^+$ reaction in searching the Z^+ baryon.

The major uncertainty in calculations of the contribution from K-meson exchange to the $pp{\to}n\Sigma^+K^+$ reaction is due to the poor knowledge of the $N\Sigma K$ coupling constants. The analysis of the available data only provides $3.5{<}g_{N\Sigma K}{<}6.4$ [12], where the upper limit stems from a dispersion analysis, which might be considered as an almost model independent evaluation of the coupling constant from data. The SU(3) limit predicts $3.2{<}g_{N\Sigma K}{<}4.6$ [13] which, within a given uncertainty, is in reasonable agreement with the $N\Sigma K$ coupling extracted from the experimental data in Ref. [12]. In the following calculations we will use $g_{N\Sigma K}$=3.86 as given by SU(3) with a mixing determined from the semileptonic hyperon decay [13].

Now, if the Z^+ baryon is a narrow state, its contribution to the total $pp{\to}n\Sigma^+K^+$ cross section is proportional to the overlap between the Z^+ spectral function (taken in Breit-Wigner form) and the phase space available. The reaction phase space R_3 increases with invariant collision energy $\sqrt{s}$ as $R_3{\propto}\epsilon^2$, where $\epsilon{=}\sqrt{s}{-}m_N{-}m_\Sigma{-}m_K$. However, the Z^+ contribution saturates at energies slightly above $\epsilon{=}M_Z{-}m_N{-}m_K{+}3\Gamma_Z{}^2$, where M_Z and Γ_Z are the mass and the width of the Z^+ resonance, respectively. Thus for M_Z=1.5 GeV the threshold for Z^+ production at its pole is $\epsilon{\simeq}66$ MeV and the optimal ratio of the Z^+ contribution to the total production cross section – due to other processes – is obtained at energies not far from threshold simply due to phase space arguments.

Obviously, a difficulty in the observation of Z^+ production in the $NN{\to}NYK$ reaction is due the dominance of other processes [14] since the contribution from the Z^+ occurs only in a small part of the available final phase space, which lies around the invariant mass of the NK system close to the Z^+ resonance mass. Thus it is important that the range of the NK invariant masses dominated by Z^+ production is not affected by the intermediate YK resonances and the NY final state interaction (FSI), because they can modify substantially the final observables relatively to the pure isotropic phase-space distributions as known both experimentally [15] and theoretically [14].

The most dominant channel in the $pp{\to}n\Sigma^+K^+$ reaction is given by the intermediate $\Delta^{++}(1920)$ resonance. Our further motivations

[2]By taking three standard deviations.

can be easily illustrated by Fig. 1, that shows the Dalitz plot for the $pp \to n\Sigma^+K^+$ reaction at an excess energy ϵ=100 MeV calculated according to Ref. [14] and additionally taking into account the FSI [16,17] as well as the Z^+ contribution. The Dalitz plot is shown as a function of the Σ^+K^+ and $n\Sigma$ invariant masses.

Furthermore, the Σ^+K^+ invariant mass distribution ranges from $m_\Sigma + m_K$ up to $m_\Sigma + m_K + \epsilon$, and is enhanced at large masses due to the $\Delta^{++}(1920)$ resonance. Notice, that large Σ^+K^+ invariant masses correspond to small $n\Sigma^+$ invariant masses that are enhanced due to the FSI [16,17]. The size of the squares in Fig. 1 is proportional to the production cross section.

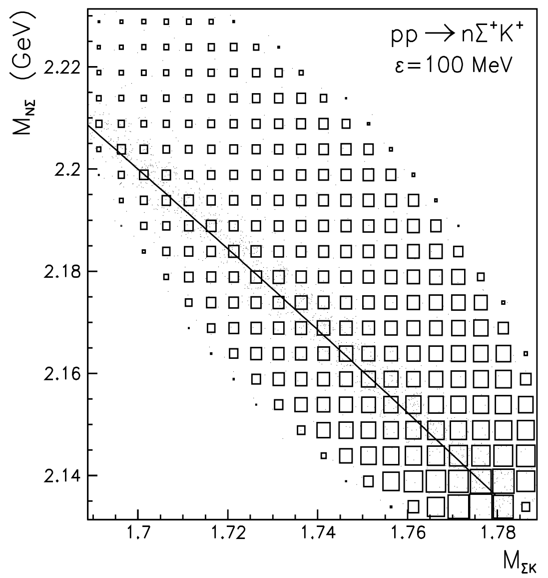

Figure 1. Dalitz plot for the $pp \to n\Sigma^+K^+$ reaction at an excess energy ϵ=100 MeV. The size of the squares are proportional to the reaction cross section. The solid line shows the trace of the Z^+ pole while the distribution along the line is due to the Z^+-baryon.

The solid line in Fig. 1 shows the trace of the Z^+ baryon pole with M_Z=1.5 GeV while the distribution along this line indicates the calculated contribution from the $Z^+ \to nK^+$ resonance assuming a width Γ=5 MeV. Note that the Z^+ contribution to the nK^+ invariant mass spectrum at $M_{NK} = M_Z$ is obtained by integrating along the solid line in Fig. 1, and in principle can be well separated from the region dominated by the $\Delta^{++}(1920)$ resonance and the FSI by applying appropriate cuts. The contribution from the Z^+ baryon then can be detected as an enhancement in the Dalitz plot along the expected Z^+ resonance pole. Indeed, as illustrated by Fig. 1, such an enhancement should be detectable.

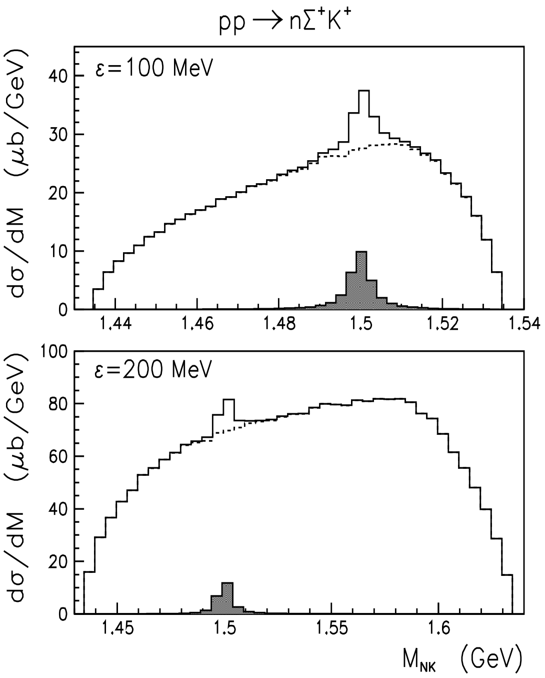

Figure 2. The invariant mass spectra for the nK^+ system produced in the $pp \to n\Sigma^+K^+$ reaction at excess energies ϵ of 100 MeV and 200 MeV. The hatched histograms indicate the contribution from the Z^+-baryon, the dashed histograms show the *background* while the solid histograms display the total spectra.

Without performing any cuts we show the invariant mass spectra of the nK^+ system produced in the $pp \to n\Sigma^+K^+$ reaction at ϵ=100 MeV and 200 MeV in Fig. 2. It is important to note that the total $pp \to n\Sigma^+K^+$ cross section calculated at ϵ=100 MeV and 200 MeV amounts to 2 μb and 12.7 μb, respectively, while the contribution from the Z^+ is around 80 nb and 120 nb, respectively.

As discussed above, the ratio of the Z^+ contribution to the total $pp{\to}n\Sigma^+K^+$ cross section substantially decreases with increasing beam energy due to phase space.

The hatched histograms in Fig. 2 show the Z^+ contribution, the dashed histograms indicate the contribution from other processes, which in the following we discuss as *background* to Z^+ baryon production. The solid histograms show the total nK^+ invariant mass spectra. The contribution from the Z^+ baryon is well visible at ϵ=100 MeV, while it becomes almost invisible at an excess energy of 200 MeV. Although the Z^+ contribution to the total $pp{\to}n\Sigma^+K^+$ cross section at ϵ=100 MeV is very small, it can be detected in the nK^+ invariant mass spectrum in case it has a narrow width. It is important to note again, that lower masses of the Z^+ baryon can be detected more easily since the *background* is reduced in this case. Opposite considerations hold for higher Z^+ masses due to a larger width and background, respectively.

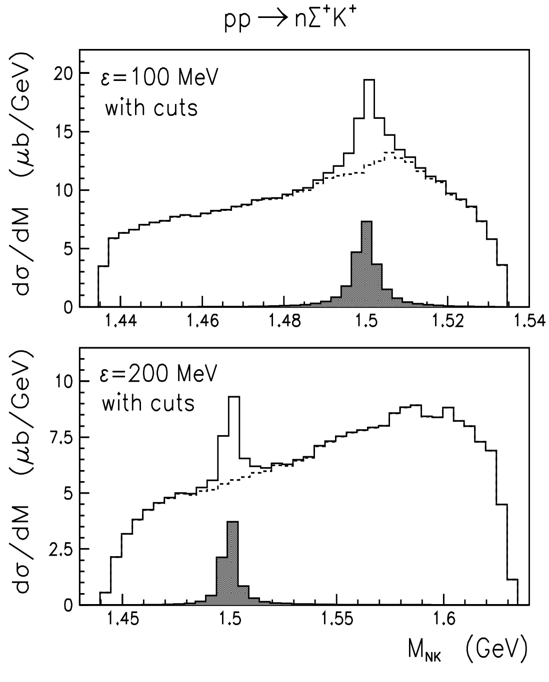

Figure 3. The same as in Fig. 2 but with cuts on the $n\Sigma^+$ and Σ^+K^+ invariant masses.

In order to improve the signal from the Z^+ baryon one can cut the regions dominated by the intermediate $\Delta^{++}(1920)$ resonance and the FSI. In this respect we show in Fig. 3 the nK^+ invariant mass spectra at ϵ=100 MeV and 200 MeV for the cuts, $M_{\Sigma K}$<1.76 MeV and $M_{N\Sigma}$>2.15 MeV. Now the Z^+ contribution becomes more pronounced even at an excess energy of 200 MeV.

In summary, the present study indicates the possibility for an observation of the penta-quark Z^+ baryon by the K^+n invariant mass spectra, produced in the $pp{\to}n\Sigma^+K^+$ reaction at excess energies around 100 MeV. Our estimate suggests that within an experimental statistics of about 200 events the Z^+ signal might be detected at $\epsilon{\simeq}100$ MeV. We note that our estimate can be considered conservative, because a small $N\Sigma K$ coupling constant, $g_{NK\Sigma} = 3.86$ [12], is used in the calculations. On the other hand, we admit that our estimate is based on a narrow Z^+ baryon width. If the Z^+ resonance has a wider width [8] or a higher mass, the data analysis of the Z^+ signal will become more uncertain.

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