A narrow "peanut" pentaquark

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Abstract. We analyse the decay $\Theta_s(1/2^+) \to NK$ in a non-relativistic Fock space description using three and five constituent quarks for the nucleon and the pentaquark, respectively. Following Jaffe and Wilczek [1], we assume that quark-quark correlations in spin-zero state play an important role for the pentaquark internal structure. Within this scenario, a strong dynamical suppression of the decay width is shown to be possible only if the pentaquark has an asymmetric "peanut" structure with the strange antiquark in the center and the two extended composite diquarks rotating around. In this case a decay width of $\simeq 1$ MeV may be a natural possibility.

The existence of pentaquarks is not yet undoubtedly established. But if these particles exist, the exotic members of the pentaquark multiplet must have a very small decay width of order 1 MeV or even lower. For the possible origin of the small pentaquark width many qualitative suggestions have been put forward. In a scenarios proposed by Jaffe and Wilczek [1] the positive-parity spin-1/2 pentaquark consists of an antiquark and two scalar diquarks in a relative P-wave state. In this talk I present the results of a fully dynamical quark-model calculation of the pentaquark width done together with B.Stech and S.Simula [2] using a non-relativistic Fock space representation for the $J^P = \frac{1}{2}^+$ pentaquark in the Jaffe-Wilczek scenario.

The decay amplitude $T(\Theta \to KN)$ is related to the matrix element

$$\begin{aligned}\langle N(p')|\bar{s}\gamma_\mu\gamma_5 d|\Theta(p)\rangle &= g_A(q^2)\bar{u}_N(p')\gamma_\mu\gamma_5 u_\Theta(p) + g_P(q^2)q_\mu\bar{u}_N(p')\gamma_5 u_\Theta(p) \\ &\quad + g_T(q^2)\bar{u}_N(p')\sigma_{\mu\nu}q^\nu\gamma_5 u_\Theta(p), \qquad q = p - p'.\end{aligned}$$

Here the form factors g_i contain poles at $q^2 > 0$ due to strange meson resonances with the appropriate quantum numbers. The residue of the pole in g_P at $q^2 = M_K^2$ is related to the amplitude of interest $T(\Theta \to NK)$: for $q^2 \to M_K^2$

$$(M_K^2 - q^2)g_P(q^2)\bar{u}_N(p')\gamma_5 u_\Theta(p) \to f_K T(\Theta \to NK),$$

where $f_K = 160$ MeV is the kaon decay constant. The form factor g_A contains the pole at $q^2 = (K_A^*)^2$, but at $q^2 = M_K^2$ it is a regular function. Making use of the relationship between the form factors g_A and g_P emerging in the limit of spontaneously broken chiral symmetry [2] gives

$$T(\Theta \to NK) = \frac{M_\Theta + M_N}{f_K} g_A(M_K^2) \cdot \bar{u}_N(p') i\gamma_5 u_\Theta(p)$$

and

$$\Gamma(\Theta) = \Gamma(\Theta \to K^+ n) + \Gamma(\Theta \to K^0 p) \simeq \frac{1}{\pi}\frac{|\vec{q}|^3}{f_K^2} g_A^2(M_K^2).$$

For $M_\Theta = 1540$ MeV one finds $|\vec{q}| = 270$ MeV and $\Gamma(\Theta) = 240\, g_A^2$ MeV. For transitions between hadrons of the same quark structure $g_A \simeq 1$ (e.g. for the nucleon $g_A \simeq 1.23$). So for a normal resonance one would expect $\Gamma(\Theta) \simeq 200$ MeV. To obtain a width of ≤ 10 MeV one needs a strongly suppressed value $g_A \leq 0.2$.

In [2] we calculated the amplitude $\langle N|\bar{s}\gamma_\mu\gamma_5 d|\Theta\rangle$ and the form factor $g_A(q^2)$ using a non-relativistic equal-time Fock space representation.

The nucleon in this framework is described by its coordinate wave function depending on the relative coordinates $\vec{\rho}_N = \vec{r}_2 - \vec{r}_3$ and $\vec{\lambda}_N = \frac{1}{2}(\vec{r}_2 + \vec{r}_3) - \vec{r}_1$, for which we take the Gaussian function

$$\Psi_N(r_1|r_2,r_3) \sim \exp\left(-\frac{1}{2\alpha_{\rho N}^2}\vec{\rho}_N^{\,2} - \frac{2}{3\alpha_{\lambda N}^2}\vec{\lambda}_N^{\,2}\right).$$

The pentaquark coordinate wave function depends on the relative coordinates $\vec{r}_{23} = \vec{r}_2 - \vec{r}_3$, $\vec{R}_{23} = \frac{1}{2}(\vec{r}_2 + \vec{r}_3)$, $\vec{r}_{45} = \vec{r}_4 - \vec{r}_5$, $\vec{R}_{45} = \frac{1}{2}(\vec{r}_4 + \vec{r}_5)$, $\vec{\rho}_\Theta = \vec{R}_{23} - \vec{R}_{45}$, $\vec{\lambda}_\Theta = \frac{1}{2}(\vec{R}_{23} + \vec{R}_{45}) - \vec{r}_1$, where $\vec{r}_1$ is the position of the strange particle, $\vec{R}_{23}$ and $\vec{R}_{45}$ are the positions of the two diquarks. As required by the quark-diquark scenario, the pentaquark coordinate wave function factorizes into the diquark wave functions and the wave function of the three-particle quark-diquar-diquark system, for which we take again Gaussian parameterizations

$$\Psi_\Theta(r_1|r_2,r_3|r_4,r_5) \sim \exp\left(-\frac{1}{2\alpha_{\rho\Theta}^2}\vec{\rho}_\Theta^{\,2} - \frac{2}{3\alpha_{\lambda\Theta}^2}\vec{\lambda}_\Theta^{\,2}\right)\exp\left(-\frac{\vec{r}_{23}^{\,2}}{2\alpha_D^2}\right)\exp\left(-\frac{\vec{r}_{45}^{\,2}}{2\alpha_D^2}\right).$$

The form factor g_A can be expressed through the following vector overlap amplitude

$$\frac{24}{\sqrt{3}}\int d\vec{r}_2 d\vec{r}_4 d\vec{r}_5 \exp\left(i\vec{q}\,\frac{\vec{r}_2+\vec{r}_4+\vec{r}_5}{3}\right)\vec{\rho}_\Theta\, \Psi_\Theta(r_s|r_2,r_d|r_4,r_5) \times \{2\Psi_N(r_2|r_4,r_5) + \Psi_N(r_4|r_2,r_5)\},$$

$$\vec{\rho}_\Theta = \frac{1}{2}(\vec{r}_2 + \vec{r}_d - \vec{r}_4 - \vec{r}_5).$$

Details of this calculation can be found in our paper [2].

Numerical estimates. We present now numerical results for the pentaquark width. Two assumptions reduce the number of parameters:

1. The structure of the diquark in the nucleon and in the pentaquark coincide, i.e. the size-parameter α_D of the diquark wave function Φ_D is equal to the parameter $\alpha_{\rho N}$ of the nucleon wave function, $\alpha_D = \alpha_{\rho N}$.

2. The parameters of the nucleon wave function are chosen such that the experimental nucleon electromagnetic form factor is reproduced for small momentum transfers, $\alpha_{\lambda N}^2/16 + \alpha_{\rho N}^2/48 = 1/M_\rho^2$. We first take a symmetric wave function $\alpha_{\lambda N} = \alpha_{\rho N} = 0.9$ fm. The diquark size parameter is then $\alpha_D = \alpha_{\rho N} = 0.9$ fm. Now only the two free parameters of the pentaquark wave function $\alpha_{\rho\Theta}$ and $\alpha_{\lambda\Theta}$ remain to be fixed. Recall that $\alpha_{\rho\Theta}$ determines the average distance between the two extended diquarks, and $\alpha_{\lambda\Theta}$ determines the average distance between the s-antiquark and the center-of-mass of the two

diquarks. Little is known about the details of the pentaquark structure. Therefore we allow the parameters $\alpha_{\lambda\Theta}$ and $\alpha_{\rho\Theta}$ to vary in a broad range $0.6\ fm < \alpha_{\lambda\Theta},\ \alpha_{\rho\Theta} < 1.6\ fm$ and study the dependence of g_A and the width on these parameters.

Fig. 1(a) shows $\Gamma(\Theta)$ vs the pentaquark size parameters $\alpha_{\lambda\Theta}$ and $\alpha_{\rho\Theta}$. If both parameters are $\simeq 1$ fm, then $g_A \simeq 0.8$ and the width is 150 MeV. No suppression due to a possible mismatch of color and flavour quantum numbers in the initial and final states takes place. However, a strong dynamical suppression occurs if the structure of the pentaquark is asymmetric: For instance, for $\alpha_{\lambda\Theta} = 0.6\ fm, \alpha_{\rho\Theta} = 1.4\ fm$, we get $g_A = 0.05$ and $\Gamma(\Theta) = 1$ MeV.

Fig. 1(b) presents $\Gamma(\Theta)$ vs the diquark size α_D for fixed values of the pentaquark size-parameters $\alpha_{\rho\Theta} = \alpha_{\lambda\Theta} = 1$ fm. A sizeable reduction of the pentaquark width occurs only for a very small diquark size which corresponds to implausibly large deviations from a symmetric nucleon wave function. Such compact diquarks are not supported by a successful description of the nucleon properties with a symmetric wave function.

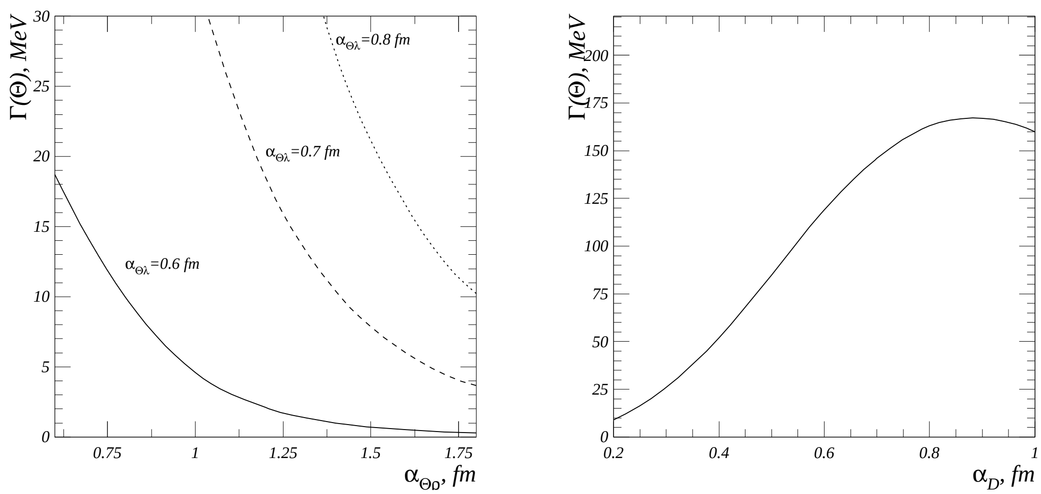

FIGURE 1. *Left (a)*: $\Gamma(\Theta)$ vs the pentaquark size parameters $\alpha_{\rho\Theta}$ and $\alpha_{\lambda\Theta}$. *Right (b)*: $\Gamma(\Theta)$ vs the diquark size parameter α_D for a symmetric pentaquark $\alpha_{\Theta\rho} = \alpha_{\lambda\Theta} = 1$ fm.

Summing up, the pentaquark decay width $\Gamma(\Theta)$ is found to depend strongly on the pentaquark configuration: when all size-parameters of the pentaquark wave function are close to 1 fm, one obtains a width of about 150 MeV, i.e. a typical hadronic value. *The color-flavour structure of the pentaquark causes no suppression of the width.*[1]

A strong dynamical suppression of the amplitude occurs for a "peanut"-shaped pentaquark, i.e. when it has an asymmetric structure with $\alpha_{\lambda\Theta} \ll \alpha_{\rho\Theta}$. For instance, $\alpha_{\lambda\Theta} = 0.6$ fm and $\alpha_{\rho\Theta} = 1.4$ fm brings the width down to 1 MeV.

We therefore conclude that *if the pentaquark can be described as a five-quark system, in which two composite spin-zero diquarks are in the relative P-wave state, the small width requires a rather asymmetric "peanut" structure with two extended diquarks rotating about the strange antiquark localized near the center*.

[1] For a discussion of the pentaquark width in the chiral limit we refer to [3].

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