Decay of Θ^+ in a quark model

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One of the distinguished features of the pentaquark particle Θ^+ is its very narrow width [1]. Many experiments so far have been reported only upper limits which are less than experimental resolution. For instance, the pioneering work of the LEPS group at SPring-8 has indicated $\Gamma \lesssim 25$ MeV [2]. Recent analysis of the K^+ scattering from the xenon or deuteron implies even smaller value $\Gamma \lesssim 1$ MeV [3, 4, 5].

In this report we study the decay of Θ^+ in the non-relativistic quark model [6]. Since we do not know the parity of Θ^+, we perform the calculation for the both cases. As we will see, the decay width depends strongly on the parity of Θ^+. Therefore, the study of the decay will help to know the parity and hence the internal structure of the pentaquarks.

In the quark model, the decay of the pentaquark occurs through the fall apart process, in which the five quarks dissociate into a three-quark cluster, a nucleon, a quark-antiquark cluster, a meson, without pair creation of the quarks [7, 8]. The decay amplitude is then written as a product of the spectroscopic factor which is the probability of finding the kaon like $q\bar{q}$ pair and the nucleon like qqq in the five quark wave function of Θ^+, and the basic interaction matrix element. For the latter, we employ the standard meson-quark interaction of the Yukawa type:

$$\mathcal{L}_{\rm int} = -i\, g\bar{\psi}\gamma_5\Phi\psi \sim \frac{g}{2m}\chi^\dagger \vec{\sigma}\cdot\vec{\nabla}\Phi\chi\,, \tag{1}$$

where we have adopted the standard notation.

The matrix element of (1) is then taken between the Θ^+ in the initial state and the kaon and nucleon in the final state:

$$\mathcal{M}_{\Theta^+\to K^+ n} = -i\sqrt{2}\langle n_f(udd)| \int d^3x\, g\bar{\psi}\gamma_5\psi e^{-i\vec{q}\cdot\vec{x}}|\Theta^+(uudd\bar{s})\rangle, \tag{2}$$

where the initial state Θ^+ can be expressed as a kaon-nucleon like state with a spectroscopic factor a: $|\Theta^+\rangle = a|(u(1)d(2)d(3))^n(u(4)\bar{s}(5))^{K^+}\rangle + \cdots$.

We have computed this matrix element for several J^P. The results are summarized in Table 1. From there, we see that the width of the negative parity Θ^+ is too wide for the state to be regarded as a sharp resonance. For the ground state configuration $(0s)^5$, this could have been expected, if we have noticed that this is the unique configuration for Θ^+. Due to this uniqueness, the Θ^+ wave function is dominated by KN like state with a strong coupling to the latter, leading to a very broad width.

For the positive parity Θ^+, the column SF (spin-flavor) shows the results for the Θ^+ configuration minimizing the spin-flavor interaction, where the spectroscopic factor is $\sqrt{5/96}$ [9]. The column SC (spin-color) is for the result for the configuration minimizing the spin-color interaction, which has a spectroscopic factor $\sqrt{5/192}$. We have also

Table 1: The $KN\Theta^+$ coupling constant $g_{KN\Theta^+}$ and decay width (in MeV) of Θ^+ for $J^P = 1/2^\pm$.

		$g_{KN\Theta}$				Γ (MeV)			
		$J^P = 1/2^-$	$1/2^+$			$J^P = 1/2^-$	$1/2^+$		
$\langle r^2\rangle^{1/2}$	α_0^2		SF	SC	JW		SF	SC	JW
$1/\sqrt{2}$ fm	3 fm^{-2}	4.1	7.7	5.5	3.2	890	63	32	11
1 fm	1.5 fm^{-2}	3.2	8.4	5.9	3.4	520	74	37	12

shown in the column JW the result for the case where the Jaffe-Wilzeck type of diquark correlation is developed [10]. In this case, the spectroscopic factor becomes $\sqrt{5/576}$ [9] instead of $\sqrt{5/96}$, which reduces the decay width by the factor 6 from the result of SF. Typically, the decay width of a positive parity Θ^+ is of order 10 MeV. To get an even narrower width $\sim$ 1 MeV, we need further mechanism.

The present analyses can be extended straightforwardly to the case of spin 3/2. For the negative parity case, the KN state must be in a d-wave, and therefore, the decay going into KN is suppressed. There could be a possible decay channel of the nucleon and the vector K^* of $J^P = 1^-$. This decay, however, is also suppressed since the total mass of the decay channel is larger than the mass of Θ^+. Hence this $J^P = 3/2^-$ state could be another candidate for the observed narrow state. This state does not have a spin-orbit partner and forms a single resonance peak around its energy.

References

[1] For an overview of the recent status, see presentations at the international workshop PENTAQUARK04 held at SPring-8, Jul. 20-23 (2004): www.rcnp.osaka-u.ac.jp/~penta04/

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