PAPER • **OPEN ACCESS**

A Theoretical Study on the Form Factors of Pentaquark States

A Theoretical Study on the Form Factors of Pentaquark States

Shukla Pal[1,5], Rismita Ghosh[2], Ballari Chakrabarti [3] and Aparajita Bhattacharya[4]

[1] Department of Physics, Basanti Devi College, Kolkata, India.
[2] Department of Physics, Jadavpur University, Kolkata, India.
[3] Department of Physics, Adamas University, Kolkata,India.
[4] Department of Physics, Jogamaya Devi College, Kolkata, India.

Author to whom any correspondence should be addressed.’: shuklaacharya123@gmail.com

Abstract. The form factors of the exotic pentaquarks such as $P_C^+(4450), P_C^+(4380), N_C^0, \Theta_C^0, \Xi_C^0$ etc. have been investigated for the momentum transfers, Q^2 in the range of $0.01 < Q^2 < 1.0$ GeV^2. The wave function from the statistical model has been used to compute the form factors. The form factors are found to decrease sharply with the increase of Q^2 in the range of $0.01 < Q^2 < 0.1$ GeV^2 which indicates the scaling violation with the gluon contribution to the form factor and the structure function whereas the form factors show gradual decrease with a small scaling violation in the range of $0.1 < Q^2 < 1.0$ GeV^2. The results have been compared with the other available theoretical and experimental data.

1. Introduction

The idea of the form factor comes from the extended structure of hadrons and deviation from the point particle behavior which also gives the idea of charge distribution of the system. In recentyears a number of exotic particles has been reported by different experimental groups. The first claim of pentaquark discovery was recorded at LEPS [1] and was named as Θ^+. The first wave of observations of pentaquark candidates containing a strange antiquark occurred in the earlyseventies for Z_0 (1780), Z_0 (1865) and Z_1(1900) [2]. Several experiments in the mid-2000s also reported discoveries of other pentaquark states.

Information about the structure of hadrons is obtained from the phenomenological experiments on electron hadron elastic scattering and electron-positron annihilation to hadron- antihadron pairs. The electromagnetic form factor as a function of momentum transfer gives usa complete description of structure. The study of properties like moments, hadronic amplitude, form factors are crucial for understanding the hadron properties and its resonances. The large contribution of magnetic moment of proton, anomalous magnetic moment of proton and anomalous magnetic moment of the neutral particle neutron demand the extended structure.A number of works has been done on the electromagnetic form factors of hadrons [3-5]. The study of form factors with momentum transfer gives us the idea of gluon contribution to the system and scaling violation. The distribution of charges, internal structure of the newly discovered pentaquark states could be studied by the theoretical investigations of the electromagnetic form factors of these exotic pentaquarks. The behavior of from factors at low and high momentum transfers suggests the internal structure. Discovery of approximate scaling in deep inelastic scattering indicates the Parton distribution and corresponding model of hadrons.

Recently reported pentaquark state $P_C^+(4450)$ and $P_C^+(4380)$ spectroscopy has been investigated in detail by Ghosh et al [6]. In the current work we have calculated the form factors of several pentaquark states such as $P_C^+(4450), P_C^+(4380), N_C^0, \Theta_C^0, \Xi_C^0$ in the framework of the Statistical Model $[7-10]$ for momentum transfers Q^2 in the range of $0.01 < Q^2 < 0.1$ GeV^2 and $0.1 < Q^2 < 1.0$ GeV^2 separately. Variations have been shown in the graphs and studied in detail. Results have been compared with the other theoretical and experimental values.

2. Formulation

The pentaquark state can be treated as composite system of a baryon and a meson ($[qqq][qq]$). To study the structure of the pentaquarks, we would like to investigate their form factors in detail. The expression of the form factor can be written as

$$F(Q^2) = \int |\Psi(r_{12})|^2 e^{i.Q.r} \cdot dr \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Q being the momentum transfer and r the radius vector with the origin at the center of the scattering system and $|\Psi(r_{12})|^2$ is the hadron wavefunction. In estimating the form factors of the pentaquark state we have used the wave function for hadrons derived in the context of statistical model $[7-10]$. The wavefunction is described as:

$$|\Psi(r_{12})|^2 = \left(\frac{8}{\pi^2 r_0^6}\right)(r_0^2 - r^2)^{3/2}(r_0 - r) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

corresponding to the harmonic type of background potential acting between the baryon and the meson. $\Theta(r_{12} - r)$ is the usual step function. Pentaquark radius $r_{12} = r_1 + r_2$ where r_1 and r_2 represent the individual radii of the baryon and the meson constituting the pentaquark respectively. With the input of the wavefunction in (1), the expression for the form factors is obtained as:

$$F(Q^2) = 48(Qr_{12}) - 3J_3(Qr_{12}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots. \qquad (3)$$

where $J_3(Qr_{12})$ is the Bessel function of the first kind. The radii of the baryon and the meson have been given input from the existing literature $[11-17]$ and have been shown in detail in the Table 1.

Table 1: Baryon and Meson Radii.

Particle	Baryon Content $[qqq]$	Radius in GeV^{-1}	Meson Content $[qq]$	Radius in GeV^{-1}
$P^{+}(4450)(p - J/\psi)$	$[uud]$	7.59	$c\bar{c}$	2.005
$P^{+}(4380)(\Delta - J/\psi)$	$[uud]$	5.997	$c\bar{c}$	2.005
$\Theta^{0}\ (p - D^{-})$	$[uud]$	7.59	$d\bar{c}$	2.7658
$N^{0}(p - D_s^{-})$	$[uud]$	7.59	$s\bar{c}$	2.2693
$\Xi^{0}(\Sigma^{-} - D_s^{-})$	$[uus]$	3.4743	$s\bar{c}$	2.2693

We have estimated the form factors of different pentaquark states for different values of Q^2 in the range of $0.01 < Q^2 < 0.1\ \mathrm{GeV}^2$ and $0.1 < Q^2 < 1.0\ \mathrm{GeV}^2$ separately. The variations of $\mathrm{F}(Q^2)$ with Q^2 for different pentaquarks such as $P_C^{+}(4450)(p - J/\psi), P_C^{+}(4380)(\Delta - J/\psi), \Theta_C^0\ (p - D^{-}), N_C^0\ (p - D_s^{-})$ and $\Xi_C^0\ (\Sigma^{+} - D_s^{-})$ have been studied in detail and have been displayed in Figure 1 and 2 . Figure 1 displays the variations of the pentaquarks in the range of Q^2 from 0 to 0.1 GeV^2 and figure 2 shows the variation from 0.1 to 1.0 GeV^2.

3. Figures and figure captions

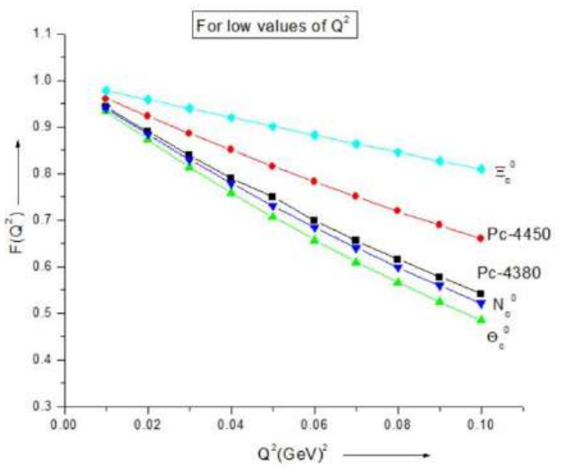

Figure 1: Form factors for low values of Q^2

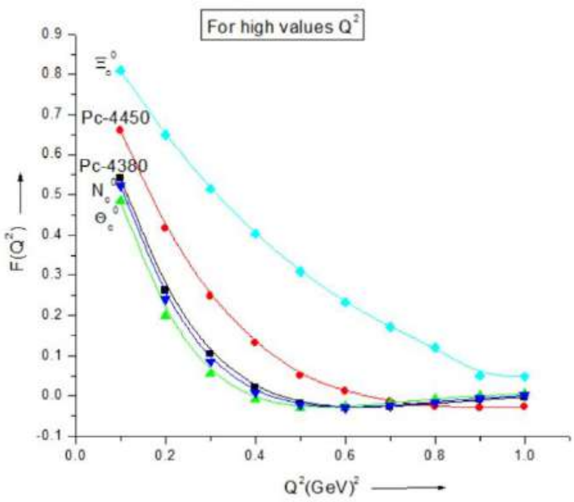

Figure 2: Form factors for low values of Q^2

4. Discussions

In the present work we have studied the form factors of the pentaquarks in the framework of statistical model. The results have been displayed in the figures. Figure 1 and Figure 2 display the variations of $\mathrm{F}(Q^2)$ with Q^2 in the range of $0.01 < Q^2 < 0.1\ \mathrm{GeV}^2$ and $0.1 < Q^2 < 1.0\ \mathrm{GeV}^2$ separately for pentaquark states. The form factors are found to be falling sharply in the range indicating a clear violation of scaling at lower values of momentum transfers. The effect may be attributed to the interaction of quarks by the exchange of gluons. Figure 1 represents the variation of the form factors for the momentum transfers in the range of $0.01 < Q^2 < 0.1\ \mathrm{GeV}^2$. The form factors show a fast decrease in the range of $0.01 < Q^2 < 0.1\ \mathrm{GeV}^2$. Form factors behavior in the Figure 2 shows an indication of

independence of the momentum transfers in the range beyond $Q^2 > 1\ GeV^2$ which may be related to the scaling behavior. Scaling strongly suggests that experimentally observed strongly interacting particles (hadrons) behave as collections of point-like constituents when probed at high energies. At high energy with improved resolution scale, scaling implies independence of the absolute resolution of the scale and effectively a point like substructure. At large energies and momentum transfers, the cross section depends on one variable only as the photon ceases to scatter coherently off the hadron but solely sees the individual as point-like partons.
In the current formulation, only the radii parameters of the corresponding exotic hadrons are needed. However, it may be mentioned that the radii of the pentaquark states have been used from our previous works [11], where we have described the pentaquark system as a baryon and a meson system and obtained very good results for the masses of the pentaquark systems. These exotic states have been recently discovered. The study of the properties like form factors is very important at this conjecture to reveal the internal structure and dynamics of the systems. In the current investigation it is observed that the newly discovered exotic hadrons show a scaling violation in the low momentum transfers. Only future experiments on these aspects would enlighten us to realize the structure and dynamics of these exotic states.

5. References

[1] Hicks K 2005 Prog. Part. Nucl. Phys. **55**, 647
[2] Trippe T G et al. [*Particle Data Group*. 1979 *Rev. Mod. Phys.* **4**, S1
[3] Sterman, G, Stoler P 1997 *Ann. Rev. Nucl.Part. Sc*. **47** 193
[4] Alexandrou, C. *PoS Lattice*, **2010**, 001
[5] Khodjamirian, A, Hadron Form Factors: From Basic Phenomenology to QCD Sum Rules 2020 CRC Press,New York.
[6] Ghosh R., Bhattacharya A, Chakrabarti B. 2015 *J. Mod. Phys.***6** 2070
[7] Bhattacharya A, Sagari, A, Chakrabarti B 2005 *Nucl. Phys. B Proc. Suppl*. **142**, 13
[8] Bhattacharya A., Chakrabarti B, Banerjee S N 1998 *Eur. Phys. J. C*, **2**, 671
[9] Bhattacharya A, Chakrabarti B, Sarkhel T, Banerjee S N 2000 *Int. J. Mod. Phys. A*, **15**, 2053
[10] Banerjee S N, Bhattacharya, Chakrabarti A, Banerjee S 2002 *Int. J. Mod. phys. A*, **17**, 4939
[11] Zhara S et al. 2018 *hep-ph: arXiv1510.09146v2*
[12] Hong C. et al. 2001 *Chi. Phys. Lett.*, **18**, 1558
[13] Hwang C W 2002 *Eur. J. Phys.*, **23**, 585
[14] Mohr P J et al. 2010 CODATA Recommended Values of the Fundamental Physical Constants. *National Institute of Standards and Technology, Gaithersburg*, 2011
[15] Alexandrou C et al. 2007 *PoSLAT* **149**
[16] Banerjee S N, Das R.K., Sarkel A 1987 *Int. J. Mod. Phy. A* **2**, 1829
[17] Bhattacharya A, Banerjee S N 1988 *Can. J. Phys.*, **66**, 749