EXOTIC HADRONS OF MINIMAL PENTAQUARK
($qqqq\bar{q}$) STATES

HAIYAN GAO

Laboratory for Nuclear Science and Department of Physics,
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

BO-QIANG MA†
CCAST (World Laboratory), P. O. Box 8730, Beijing 100080, China
and
Institute of High Energy Physics, Academia Sinica, Beijing 100039, China

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It is shown that the exotic non-$qqq$ hadrons of pentaquark $qqqq\bar{q}$ states can be clearly distinguished from the conventional $qqq$-baryon resonances or their hybrids if the flavor of $\bar{q}$ is different from any of the other four quarks. We suggest the physical process $p(e,e'K^-)Z(uudd\bar{s})$, which can be investigated at the Thomas Jefferson National Accelerator Facility (JLab), as an ideal process to search for the existence or non-existence of the exotic hadron of minimal pentaquark state $Z(uudd\bar{s})$.

The search for the existence of $Z(uudd\bar{s})$ is also discussed in the paper.\*a

The quark model\[1\] has been proved to be remarkably successful in classifying the mesons and baryons as composite systems of quark-antiquark ($q\bar{q}$) states for mesons and three quark ($qqq$) states for baryons.\[2\] Also, it has been well known that the structure of hadrons should be more complicated than the simple lowest valence quark states, and there are additional sea quark-antiquark pairs and gluons inside the hadrons probed by various deep inelastic processes. The situation can be well illustrated by the structure of the nucleon in terms of quark-gluon components as supported by a large number of phenomenological evidence. The existence of the higher quark-gluon components in the nucleon structure can be described by perturbative quantum chromodynamics (pQCD) for the perturbative aspect and perhaps by the baryon-meson fluctuation configuration\[3\] for some of the non-perturbative aspects. Therefore a conventional baryon should be composed of various quark-gluon configurations in which the lowest is the three quark ($qqq$) state. From another point of view, there have been various theoretical and experimental investigations on the

\*a We added this sentence after the original published form of this paper.
possibility of the existence of exotic hadrons beyond the conventional quark model spectroscopy, such as multiquark mesons \((qqq\bar{q})\) and baryons \((qqqqq\bar{q})\), dibaryons \((qqqqqq\bar{q})\), hybrid states \((q\bar{q}g)\), and glueballs. The present situation seems to be very promising for the existence of the hybrid states and glueballs. Though much progress has been made and many candidates for the other exotic hadrons have been reported, the existence of the exotic hadrons of multiquark states is still far from being clear, due to the difficulty to clearly distinguish candidates from a large number of various possible meson and baryon resonances.

In this letter we will focus our attention on the exotic hadrons composed of five quarks, i.e., a new class of particles of minimal pentaquark \((qqqq\bar{q})\) states. There have been several candidates for the pentaquark states, such as \(\Lambda(1405)\) and the possible existence of the pentaquark baryons of hidden strangeness \(X(2050)\) and \(X(2000)\), and several possible narrow states which might be pentaquark states. The \(\Lambda(1405)\) has been confirmed to exist, but it is still not clear whether it is a three quark \(uds\) state resonance or a baryon-meson state. The existence of several other possible pentaquark states still needs to be confirmed. Although these possible particles may have properties different from conventional \(qqq\)-baryon, it is difficult to identify them unambiguously from possible baryon resonances or their hybrids. In the following we will show that the pentaquark \((qqqq\bar{q})\) states with the antiquark \(\bar{q}\) having different flavor from any of the other four quarks have the unique property of no place in the spectroscopy of the \(qqq\)-baryon quark model, and can not be misidentified with any of the baryon resonances or hybrids. Thus, they might be helpful to clarify the present situation concerning \(\Lambda(1405)\) and to confirm the existence of the pentaquark states if any evidence for such a hadron can be observed.

For simplicity, we will consider the pentaquark \((qqqq\bar{q})\) states as composite systems of baryon-meson states, inspired by our understanding of the non-perturbative sea quark-antiquark pairs of the nucleon in terms of baryon-meson fluctuations. Although the baryon-meson states can not fully accommodate all possible pentaquark states, it will be sufficient as a first approximation to see whether it provides the hint for a new class of particles. It has been pointed out that the lowest baryon-meson fluctuations of the nucleon can provide a comprehensive understanding of a number of empirical anomalies, such as the violation of the Gottfried sum rule, the large excess of charm quarks at large Bjorken \(x\), the strange quark-antiquark distribution asymmetry, and the violation of the Ellis-Jaffe sum rule. Thus any of the conventional baryons in the quark model should have an important part of baryon-meson components beyond the three valence quark \(qqq\)-states. Such baryon-meson fluctuations are of non-perturbative nature and can be handled by models at the moment, but their existence can be verified and studied from various experiments. There are also theoretical studies which show that the \(\Lambda(1405)\) may be dominated by baryon-meson terms in the wavefunctions. Also it has been found that there is increasing empirical support for an \(\eta\)-baryon octet of \(J^P = \frac{1}{2}^-\) states associated with the \(S\)-wave \(\eta + N\) \([N(1535)], \eta + \Lambda\) \([\Lambda(1670)], \eta + \Sigma\) \([\Sigma(1750)]\) threshold interactions. These results naturally inspire us to consider the possible
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existence of a new class of particles in terms of baryon-meson states. Some of these baryon-meson states can be served as the intrinsic quark-antiquark sea components in the ordinary $qqq$-baryons and they mix with the ordinary baryons, but we will show that some pentaquark ($qqqqq$) states in terms of meson-baryon states can not find their place in the conventional three quark ($qqq$) baryon spectroscopy.

We notice that in case the antiquark has the same flavor (e.g., $q_4$) with any of the other four quarks in the pentaquark $q_1q_2q_3q_4q_4$ state, such pentaquark state may be easily identified with the three quark state of $q_1q_2q_3$-baryon resonance, from the above knowledge that any baryon of $q_1q_2q_3$ valence states may have higher quark components of $q_1q_2q_3q_4q_4$ states. We also notice that all of the previous reported candidates of pentaquark states belong to such $q_1q_2q_3q_4q_4$ states with hidden flavor $q_4$, thus they are difficult to be distinguished from possible $q_1q_2q_3$-baryon resonances with exotic properties. A completely unambiguous way of identifying a pentaquark $qqqq$ state is that the antiquark $\bar{q}$ having flavor different from any of the other four quarks. We find that such pentaquark states can not exist in the quark model $qqq$-baryon spectroscopy. Thus, they have the unique property of minimal configuration $qqqqq$ to be distinguished from the conventional baryons.

Such minimal pentaquark states composed of the light flavor up ($u$) and down ($d$) quarks can only exist in two possible states: $uudd$ and $ddud$, which can be considered as composite systems of $\Delta^+ (uuu)\pi^+ (ud)$ and $\Delta^- (ddd)\pi^- (du)$. We find that it is not easy to find good processes which can produce such particles conveniently. There are more such minimal pentaquark states composed of three flavor $u$, $d$, and $s$ (strange) quarks (but with only one $\bar{s}$ or $s$ quark): $uuus$, $uuuds$, $uudds$, $uddds$, $dduds$, $ddusu$, and $uusu$. When consider them in terms of baryon-meson states, those in which the baryon is the nucleon should be: $uuus = p(uud)K^+(us)$, $uuuds = n(udd)K^0(ds)$, and $uudds = n(udd)K^0(su) = p(uud)K^0(ds)$. From which we notice that the minimal pentaquark states which can be easily measured might be $uuuds = p(uud)K^+(us)$ and $uudds = n(udd)K^0(us)$, which might be produced from physical processes $p(e,e'K^-)Z(uuuds)$ and $n(e,e'K^-)Z(uudds)$ \(^b\) which can be measured at the Thomas Jefferson National Accelerator Facility (JLab). As far as we know, there have been theoretical studies on the properties of the pentaquark states in the MIT bag model \(^1\) and in other frameworks \(^2\). The pentaquark states we suggest to measure are the ones with strangeness number $S = 1$ (i.e., with an anti-strange quark inside the hadron), a distinct quantum number that can not be possessed by ordinary baryons in the conventional quark model spectroscopy. There have been also suggestions for the possible existence of other exotic multi-quark states, such as $\bar{c}sq\bar{q}$ and $\bar{c}sqqq$ with both strangeness and charm \(^3\). However, there is still no convincing experimental evidence for the existence of the above mentioned minimal pentaquark states such as $Z(uuuds)$.

There should be a number of physical processes that could in principle produce the minimal pentaquark state $Z(uuuds)$, such as $p(\gamma, K^-)Z(uuuds)$,

\(^b\)Since there is no free neutron target, deuterium targets should be used in this case.
p(p, p′K−)Z(uuud̄̄s), and p(π+, K0)Z(uuud̄̄s) et al. The p(e, e′K−)Z(uuud̄̄s) process at JLab is ideal for this physics because of the large luminosity that can be obtained and the fine resolutions of the spectrometers. Furthermore, the continuous-wave electron beam significantly enhances the signal to background ratio for coincidence measurement. The advantage at JLab is that there is no need to build new detector to search for the new particle Z(uuud̄̄s), since the existence or non-existence of Z(uuud̄̄s) can be re-constructed using the missing mass technique by detecting the scattered electron and the final state K− in coincidence. We do not need to know the explicit properties, such as the life time, width, mass, spin, parity, and decay modes et al. for detecting such particle.

We now estimate the probability of producing Z(uuud̄̄s) from the proton target by employing the baryon-meson fluctuation model of the nucleon sea. We check the probability of finding the quark configuration of uuud̄̄s and s̄ū inside the proton. From the discussion of the strangeness content of the nucleon sea, we know that the lowest baryon-meson fluctuation of the strange quark-antiquark pairs is p(uuud̄̄s) = Λ(uds)K+(uś) and the probability of finding such fluctuation should be on the order 3%. We also know from the Gottfried sum rule violation that the dominant baryon-meson fluctuation of the proton is p(uudd̄̄) = n(udd)π+(ud) and the probability of finding such fluctuation should be on the order 15%. From the SU(3) symmetry of octet baryons, we can estimate the probability of finding the baryon-meson fluctuation Λ(udsu) = p(uud)K−(s̄ū) inside Λ as around 10%. Thus the probability of finding the baryon-meson-meson fluctuation p(uudusu) = Λ(udusu)K+(uś) = p(uud)K−(s̄ū)K+(uś) of the proton should be around 3% · 10% = 0.3% from a convolution picture, as shown in Fig. 1. When the K−(s̄ū) is knocked out by the incident electron beam, the left spectator should be of the quark configuration p(uud)K+(uś) = uuud̄̄s, which is the same as that of the pentaquark state Z(uuud̄̄s). From above discussion, we can estimate the cross section for the process p(e, e′K−)Z(uuud̄̄s) by largest as around 0.1 times that of the process p(e, e′K+)Λ by removing the kinematical factors, provided with the assumption that the left spectator keeps as a single state particle Z(uuud̄̄s). In fact, the real situation might be not so optimistic as the best case estimated above.

Since the five quarks of Z(uuud̄̄s) might be grouped into clusters rather than confined inside a bag, we still have difficulty predicting the mass of the minimal pentaquark state Z(uuud̄̄s), and it is likely below or slightly above the threshold of two free particle state of p and K+, i.e., M = 1432 MeV, if such particle can exist in the laboratory. If the mass of Z(uuud̄̄s) is above M = 1432 MeV, such particle should have a short life time and a broad width. Also there should be large background contribution above the threshold of p(e, e′K−)K+p to the p(e, e′K−)Z(uuud̄̄s) process. Therefore the resolutions required for the experiment on Z(uuud̄̄s) are high. In this situation, the new particle Z(uuud̄̄s) might also be possible to be produced and measured in the resonance channel K+p → Z(uuud̄̄s) → K+p by reconstructing the Z(uuud̄̄s) from the detected final state K+p and p, provided with
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Fig. 1. The possible mechanism to produce the exotic minimal pentaquark state $Z(uuuds)$ by the electroproduction of $K^-$ from the proton target, i.e., the physical process $p(e, e'K^-)Z(uuuds)$.

good resolutions. In case $\Lambda(1405)$ is a minimal pentaquark state with configuration $\Lambda(1405) = X(uuuds) = p(uud)K^- (s\bar{u})$ or $\Lambda(1405) = X(udds\bar{d}) = n(udd)K^0 (s\bar{d})$, we may even consider the possibility that $Z(uuuds) = p(uud)K^+ (u\bar{s})$ is one of the partner particles of $\Lambda(1405)$ and make a clear prediction of its mass $M \approx 1405$ MeV. It would be relatively easy to be measured from $p(e, e'K^-)Z(uuuds)$ process if the mass of $Z(uuuds)$ is below 1432 MeV. The possible channels for the background contribution should be $p(e, e'K^-)\Delta^{++}$ and $p(e, e'K^-)\pi^+ p$ which involve the Cabibbo suppressed weak interaction below the threshold of the process $p(e, e'K^-)K^+ p$, and such contributions are small. The re-construction of $Z(uuuds)$ would be clean without significant background contribution. Thus any evidence for or against the existence of $Z(uuuds)$ might be also helpful in clarifying the situation concerning $\Lambda(1405)$.

We can not exclude the possibility that only certain specific pentaquark states, not all of them, can exist in nature. For example, the existence of $Z(uuuds)$ is more possible than that of $Z(uuuds)$ considering the fact that the stable pentaquark states may carry less net charge.\(^5\) We can extend the study in this direction by systematic exploration of various minimal pentaquark states with configurations pointed out above, such as to search for $Z(uuuds)$ from the physical process $D(e, e'K^- p)Z(uuuds)$ or $D(e, e'\Lambda)Z(uuuds)$ at JLab. It is interesting to note a recent suggestion\(^{15}\) on the search for such a $Z(uuuds)$ particle from the $pp \rightarrow n\Sigma^+ K^+$ reaction by analyzing the $nK^+$ invariant mass spectrum. We also point out here that the search of the existence of the exotic new particle $Z(uuuds)$ can be combined with the planned program of the physical process of $p(e, e'K^- K^+) p$ at JLab. Thus the search of new particles $Z(uuuds)$ and $Z(uuuds)$ at JLab is not necessarily in conflict with conventional studies, even though the chance of finding such particles might be small. From another point of view, even the confirmation of the non-existence of $Z(uuuds)$ and $Z(uuuds)$ can enrich our understanding of the hadronic structure and the strong interaction.

\(^{6}\)However, the proton with charge 1 is more stable than the neutron with charge 0.
In summary, we proposed in this letter the idea of the possible existence of exotic hadrons of minimal pentaquark \(qqqq\bar{q}\) states such as \(Z(uuuds)\). We found that the exotic hadrons of pentaquark \(qqqq\bar{q}\) states can not find place in the conventional quark model spectroscopy of \(qqq\)-baryons if the flavor of \(\bar{q}\) is different from any of the other four quarks, thus such minimal pentaquark states can be clearly identified as a new class of particles if there is any evidence for the existence. We also discussed the possible configurations for such minimal pentaquark states and pointed out that \(Z( uuuds)\) might be identified. We suggested the physical process \(p(e,e'K^-)Z(uuuds)\), which can be studied at JLab, as an ideal process to search for the existence or non-existence of the exotic pentaquark hadron \(Z(uuuds)\). The possibility of a search for the \(Z(uudd\bar{s})\) state from the physical process \(D(e,e'K^-p)Z(uudd\bar{s})\) or \(D(e,e'\Lambda)Z(uudd\bar{s})\) at JLab is also pointed out. Further theoretical and experimental explorations are required to support or rule out the existence of such exotic minimal pentaquark states which have no place in the conventional \(qqq\)-baryon spectroscopy.

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