PENTAQUARK BARYON PRODUCTION IN NUCLEAR REACTIONS *

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Using a hadronic model with empirical coupling constants and form factors, we have evaluated the cross sections for the production of exotic pentaquark $^{\Theta^+}$ and/or $^{\Xi^+_5}$ and $^{\Xi^-_5}$ in reactions induced by photons, nucleons, pions, and kaons on nucleon targets. We have also predicted the $^{\Theta^+}$ yield in relativistic heavy ion collisions using a kinetic model that takes into account both $^{\Theta^+}$ production from the coalescence of quarks and antiquarks in the quark-gluon plasma and the effects due to subsequent hadronic absorption and regeneration.

1. Introduction

One of the most exciting recent experimental results in hadron spectroscopy is the narrow baryon state that was inferred from the invariant mass spectrum of $K^+n$ or $K^0p$ in nuclear reactions induced by photons $^1$, kaons $^2$, and protons $^3$. The extracted mass of about 1.54 GeV and width of less than 21-25 MeV are consistent with those of the pentaquark baryon $^{\Theta^+}$ consisting of $uudds$ quarks and predicted in the chiral soliton model $^4$. However, the reported large width is limited by experimental resolutions as the actual width is expected to be much smaller $^5$. Its existence has also been verified in the Skyrme model $^6$, the chiral quark model $^7$, the constituent quark model $^8$, the QCD sum rules $^9$, and the lattice QCD $^{10}$. Although most models predict that $^{\Theta^+}$ has spin 1/2 and isospin 0, their predictions on $^{\Theta^+}$ parity vary widely. While the soliton model gives a positive parity and the lattice QCD studies favor a negative parity, the quark model can give either positive or negative parities, depending on whether quarks are

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correlated or not. To help determine the quantum numbers of $\Theta^+$, studies have been carried out to understand its production mechanism in these reactions $^{11,12}$. Using a hadronic model with empirical coupling constants and form factors, we have evaluated the cross sections for $\Theta^+$ production from these reactions $^{13,14,15}$ and also those for other multistrange exotic pentaquark baryons $\Xi^+_5(uussd)$ and $\Xi^-_5(ddssu)$ $^{16}$. The latter has been observed in proton-proton collisions at center-of-mass energy of 17.2 GeV by the NA49 Collaboration at SPS $^{17}$, with mass 1.86 GeV and width about 18 MeV due to detector resolution. Moreover, the yield of $\Theta^+$ in heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC) has been studied using the quark coalescence model $^{18}$. In this talk, we report the results from our studies.

2. $\Theta^+$ production in photonucleon reactions

![Diagram](image)

Figure 1. Diagrams for $\Theta^+$ production from the reaction $\gamma n \rightarrow K^-\Theta^+$.

For $\Theta^+$ production from photonucleon reactions, possible processes are $\gamma p \rightarrow K^0\Theta^+$, $\gamma n \rightarrow K^-\Theta^+$, $\gamma p \rightarrow K^*0\Theta^+$, and $\gamma n \rightarrow K^*\Theta^+$. As an illustration, we show in Fig.1 four possible diagrams for the reaction $\gamma n \rightarrow K^-\Theta^+$, involving the $t$-channel $K$- and $K^*$-exchange, the $s$-channel nucleon pole, and the $u$-channel $\Theta^+$-exchange. To evaluate their amplitudes, we need the photon coupling to $\Theta^+$ as well as the coupling constants $g_{NK\Theta}$ and $g_{NK^*\Theta}$, besides the well-known couplings of photon to $K^-$, $K^*$, and neutron. Since the anomalous magnetic moment of $\Theta^+$ is not known empirically and theoretical estimates give a much smaller value than that of nucleons $^{12,19}$, we have neglected its contribution and included only the coupling of photon to the charge of $\Theta^+$. For the coupling constant $g_{KNE\Theta}$, it is proportional to the square root of $\Theta^+$ width and depends on the spin and parity of $\Theta^+$. Taking the $\Theta^+$ width to be 1 MeV, which is consistent with available $K^+N$ and $Kd$ data $^5$, we then have $g_{KNE\Theta} \approx 1$ if $\Theta^+$ has spin 1/2 and positive parity. It is reduced to $g_{KNE\Theta} \approx 0.14$ if the $\Theta^+$ parity is negative due to the absence of a centrifugal barrier between nucleon and kaon.
the reaction suitable contact term in the interaction Lagrangian, the cross section for restoring the gauge invariance of resulting total amplitude by adding a parameter $\Lambda \approx \sqrt{3} g_{K\pi} \Theta^+$ is determined from fitting the measured cross sections at photon energy $E_\gamma = 3 \text{ GeV}$, that is determined from fitting the measured cross sections at photon energy $E_\gamma = 3 \text{ GeV}$ are about 30 nb and 15 nb.

Figure 2. Total (upper panels) and differential (lower panels) cross sections for $\Theta^+$ production from photo-nucleon reactions.

To take into account the finite sizes of hadrons, we have included for each amplitude a form factor of the form $F(x) = \Lambda^4 / [\Lambda^4 + (x - m_x^2)^2]$, where $x = s, t$, and $u$ with corresponding masses $m_x = m_N, m_K$ or $m_{K^*}$, and $m_\Theta$ of the off-shell particles at strong interaction vertices.

After restoring the gauge invariance of resulting total amplitude by adding a suitable contact term in the interaction Lagrangian, the cross section for the reaction $\gamma n \to K^- \Theta^+$ has been evaluated in Ref. 15 with a cutoff parameter $\Lambda \approx 1.2 \text{ GeV}$, that is determined from fitting the measured cross section for charmed hadron production from photon-proton reactions with two-body final states. The resulting total and differential cross sections for the reaction $\gamma n \to K^- \Theta^+$ are shown in the leftmost panels of Fig. 2.
with and without $K^*$ exchange, respectively, and the produced $\Theta^+$ peaks at forward direction in the center-of-mass system. For negative parity $\Theta^+$, the cross section is reduced by about a factor of 10, although the coupling constant $g_{KN\Theta}$ is about a factor of 7 smaller than that for positive parity $\Theta^+$, and the angular distribution remains forward peaked.

The cross sections for $\Theta^+$ production from other photon-nucleon reactions $\gamma p \rightarrow \bar{K}_0^0\Theta^+$, $\gamma n \rightarrow K^* - \Theta^+$, and $\gamma p \rightarrow \bar{K}_0^*\Theta^+$ can be similarly evaluated, and their cross sections are shown in other panels of Fig.2. The cross section of about 35 nb for the reaction $\gamma p \rightarrow \bar{K}_0^0\Theta^+$ at $E_\gamma = 3$ GeV is comparable to the revised value of about 50 nb measured in SAPHIR experiment at Bonn Electron Stretcher Accelerator.

3. $\Theta^+$ production in proton-proton reactions

![Diagram](image)

Figure 3. Diagrams (left panels) and cross sections (right panel) for $\Theta^+$ production from the reaction $pp \rightarrow \Sigma^+\Theta^+$.

For $\Theta^+$ production in proton-proton reactions, possible diagrams are shown in the left panels of Fig.3 involving both $t$- and $u$-channel exchange of $K$ and $K^*$. The coupling constants $g_{KN\Sigma} \approx -3.78$ and $g_{K^*N\Sigma} = 3.25$ are obtained from well-known $g_{\pi NN} = 13.5$ and $g_{\rho NN} = 3.25$ by SU(3) relations. The form factors at interaction vertices are taken to be $F(q^2) = \Lambda^2/(\Lambda^2 + q^2)$, with $q$ being the three momentum of exchanged $K$ or $K^*$. Using a cutoff parameter $\Lambda = 0.42$ GeV, obtained from fitting the experimental cross sections for the reactions $pp \rightarrow K^+\Lambda p$ and $pp \rightarrow D^+\Lambda_c p$ with similar hadronic models, the resulting cross section for the reaction $pp \rightarrow \Sigma^+\Theta^+$ is shown in the right panel of Fig.3 for $g_{KN\Theta} = 1$ and different values of $g_{K^*N\Theta}$. The value of 0.3 $\mu$b obtained with $g_{K^*N\Theta} = 1.0$ at center-of-mass energy $\sqrt{s} = 2.75$ GeV, corresponding to a beam momentum
\[ p_{\text{beam}} = 2.95 \text{ GeV/c}, \] is comparable to the 0.4 \( \mu \text{b} \) measured in the COSY experiment.

4. \( \Theta^+ \) production in pion- and kaon-nucleon reactions

\[ \begin{align*}
\Theta^+ & \rightarrow K^+ + \pi^- \\
\pi^+ & \rightarrow K^+ + \pi^0
\end{align*} \]

Figure 4. Diagrams for \( \Theta^+ \) production from the reactions \( \pi N \rightarrow \bar{K}^{\Theta^+} \) (left two panels) and \( KN \rightarrow \pi^{\Theta^+} \) (right two panels).

For \( \Theta^+ \) production from the reactions \( \pi N \rightarrow \vec{K} \Theta^+ \) and \( KN \rightarrow \pi \Theta^+ \), the relevant diagrams are shown in Fig. 4. Using additional known empirical coupling constant \( g_{\pi KK} = 3.28 \) and similar form factors as in the reaction \( pp \rightarrow \Sigma^+ \Theta^+ \), their cross sections are shown in the left two panels of Fig. 5 with values of 0.5-5 \( \mu \text{b} \) for \( \pi N \rightarrow \vec{K} \Theta^+ \) and 20-75 \( \mu \text{b} \) for \( KN \rightarrow \pi \Theta^+ \) at center-of-mass energy of 0.2 GeV above their respective threshold energies. It will be interesting to compare the predicted cross sections with future data from experiments that are being carried out at KEK in Japan.

5. \( \Xi^+_5 \) and \( \Xi^-_5 \) production in photonucleon reactions

For \( \Xi^+_5 \) production in photonucleon reactions, the relevant diagrams are shown in Fig. 6. The needed additional coupling constants \( g_{K\pi \Sigma^{(0)}} \) can
be obtained from the SU(3) relations $g_{K(K^*)\Sigma\Xi_5} = g_{K(K^*)N\Theta}/\sqrt{2}$ if $\Theta^+$ and $\Xi_5$ belong to the same antidecuplet. Introducing appropriate form factors with empirical cutoff parameters, the resulting cross section for the reaction $\gamma p \rightarrow K^0K^0\Xi_5^+$ together with that for the reaction $\gamma n \rightarrow K^+K^+\Xi_5^-$ are shown in the right two panels of Fig. 5 for $g_{K\Sigma\Xi_5} = 0.71$ but different values of $g_{K^*\Sigma\Xi_5}$. The cross sections are about 0.01-0.1 nb at photon energy $E_{\gamma} = 4.5$ GeV, and this information will be useful for planning experiments to verify these exotic multistrange pentaquark baryons in photonucleon reactions.

6. $\Theta^+$ production in relativistic heavy ion collisions

The quark-gluon plasma formed in heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC) provides a promising environment for producing hadrons consisting of multiple quarks such as the pentaquark baryons. Based on the quark coalescence model for hadron production from the quark-gluon plasma, which has been shown to give a consistent description of the observed large baryon/meson ratio at intermediate transverse momenta of about 3 GeV/c and scaling of hadron elliptic flows according to their constituent quark content, we have evaluated the yield of $\Theta^+$ in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. With a plasma of quarks of constituent masses and massive gluons at temperature $T_c = 175$ MeV and in a volume $\sim 1000$ fm$^3$ as in Ref. 26, the resulting $\Theta^+$ number is about 0.19 if $\Theta^+$ has a radius of $\sim 0.9$ fm, and is somewhat smaller than that predicted by the statistical model. To take into account subsequent hadronic effects due to the reactions $\Theta \leftrightarrow KN$, $\Theta\pi \leftrightarrow KN$, and $\Theta\bar{K} \leftrightarrow \pi N$, a schematic isentropic expanding fireball model has been used.

Using the cross sections evaluated in previous sections, the time evolution of the $\Theta^+$ abundance has been studied for different values of $\Theta^+$ width or coupling constant $g_{K_N\Theta}$. The final $\Theta^+$ yield increases to about 0.5 for $\Gamma_\Theta = 20$ MeV but remain about 0.2 for $\Gamma_\Theta = 1$ MeV. Similar ef-
fects are seen if the number of $\Theta^+$ produced from the quark-gluon plasma is increased to 0.94, resulting from a $\Theta^+$ radius that is 30% larger, or decreased to zero. With the expected small $\Theta^+$ width, the hadronic effect is thus small, and the abundance of $\Theta^+$ is then sensitive to its production from the quark-gluon plasma. Since the baryon chemical potential in the quark-gluon plasma is small, the yield of anti-$\Theta$ is only slightly less than that of $\Theta^+$.

7. Summary

We have studied exotic pentaquark baryon production both in elementary reactions involving photons, protons, pions, and kaons on nucleon targets and in relativistic heavy ion collisions. With a phenomenological hadronic model, cross sections for the elementary reactions are evaluated by taking into account the coupling of $\Theta^+$ to both $KN$ and $K^*N$. Assuming that $\Theta^+$ has positive parity and a width of 1 MeV, corresponding to a coupling constant $g_{K^*N\Theta} \approx 1$, and depending on the value of $g_{K^*N\Theta}$, the cross sections are 4-35 nb for $\gamma p \rightarrow \bar{K}^0\Theta^+$, 15-30 nb for $\gamma n \rightarrow K^-\Theta^+$, 4-15 nb for $\gamma p \rightarrow K^*\Theta^+$, and 5-150 nb for $\gamma n \rightarrow K^*\Theta^+$ at photon energy $E_\gamma = 3$ GeV; 0.1-2 $\mu$b for $pp \rightarrow \Sigma^+\Theta^+$, 0.5-5 $\mu$b for $\pi N \rightarrow K\Theta^+$, and 20-75 $\mu$b for $KN \rightarrow \pi\Theta^+$ at center-of-mass energy of 0.2 GeV above their threshold. The produced $\Theta^+$ in these reactions all peaked at forward angles in the center-of-mass system. The cross sections are smaller by about an order of magnitude if $\Theta^+$ has negative parity. For multistrange pentaquark baryons $\Xi^+_5$ and $\Xi^-_5$, the cross sections for their production in the reactions $\gamma p \rightarrow K^0\bar{K}^0\Xi^+_5$ and $\gamma n \rightarrow K^-K^+\Xi^-_5$ are 0.01-0.1 nb at photon energy $E_\gamma = 4.5$ GeV. In heavy ion collisions at RHIC, about 0.19 $\Theta^+$ is produced during hadronization of the quark-gluon plasma, but the final number after hadronic absorption and regeneration depends on the width of $\Theta^+$. These results are useful for understanding not only the experimental data but also the properties of pentaquark baryons.

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