Photoproduction evidence for and against hidden-strangeness states near 2 GeV

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(Submitted to Phys. Rev. D1)

(November 12, 2018)

Abstract

Experimental evidence from coherent diffractive proton scattering has been reported for two narrow baryonic resonances which decay predominantly to strange particles. These states, with masses close to 2.0 GeV would, if confirmed, be candidates for hidden strangeness states with unusual internal structure. In this paper we examine the literature on strangeness photoproduction, to seek additional evidence for or against these states. We find that one state is not confirmed, while for the other state there is some mild supporting evidence favoring its existence. New experiments are called for, and the expected photoproduction lineshapes are calculated.

PACS numbers: 13.60.Rj, 14.20.Gk, 13.85.Hd, 13.30.Eg
I. INTRODUCTION

Experimental claims of new, possibly-exotic states must always be treated with skepticism and caution. This is especially true when the structure or quantum numbers of the claimed states are not established. A traditional verification test is to seek evidence of their existence in reaction channels different than those of the original claim. In this paper I wish to shed additional light on a pair of fairly narrow baryonic resonances which have been reported recently by the SPHINX collaboration working at IHEP [1].

The two states were seen in coherent diffractive production using 70 GeV protons on a carbon target in the reactions:

\[ p + C \rightarrow [\Sigma^0 + K^+] + C \]  \hspace{1cm} (1.1)

and

\[ p + C \rightarrow [\Sigma^0(1385) + K^+] + C \]  \hspace{1cm} (1.2)

where the brackets signify that the signal was seen in the invariant mass spectra of these strange particles. Coherent production off the nucleus was isolated by cutting on low transverse momentum, \( p_T \), of the produced particles. In the first case, for \( p_T^2 < 0.1 \text{ GeV}^2 \), a structure labeled \( X(2000) \) was identified in the \( K^+\Sigma^0 \) invariant mass spectrum with \( M = 1996\pm6 \text{ MeV} \), and \( \Gamma = 99\pm17 \text{ MeV} \). (A more recent and complete set of results from this group were discussed by L. Landsberg at the PANIC '96 Conference [2]; here the numbers were slightly revised to \( M = 1996\pm7 \text{ MeV} \), and \( \Gamma = 99\pm21 \text{ MeV} \).) In the second case, for \( p_T^2 < 0.02 \text{ GeV}^2 \), a structure labeled \( X(2050) \) was identified in the \( K^+\Sigma^0(1385) \) invariant mass spectrum with \( M = 2052\pm6 \text{ MeV} \), and \( \Gamma = 35^{+22}_{-35} \text{ MeV} \). The apparent width of the \( X(2050) \) state was consistent with the mass resolution of the experiment. No signal for these states was seen in the non-coherent part of the data, i.e. at larger transverse momentum. No further analysis to uncover the spin, isospin or angular distributions of these states was presented.
Both the $X(2000)$ and $X(2050)$ structures are quite narrow for such massive baryonic resonances, where typical widths are several hundred MeV. If these states are confirmed, their narrowness hints at unusual internal structure. Furthermore, the states were seen to decay predominantly to strange particles, with no positive signal seen in other final states such as $\Delta\pi, p\pi\pi$, and $\Lambda K$. Most nucleon resonances have strange-particle decay branches in the range of a few percent (for those few cases where these branches have been measured). Golovkin et al. [1] quoted lower limits on the order of unity for branching ratio measurements of the $K\Sigma$ decays to the other decay channels. The dominance of the strange-particle decays of these states was cited as another unusual feature of these states. The authors interpreted the states as 5-quark exotics containing valence $s - \bar{s}$ quark pairs, and hypothesized that the states may be examples of $(qqq) - (q\bar{q})$ structures with color-octet bonds, or $(qq) - (qq\bar{q})$ with color-sextet bonds [3]. In this interpretation, the narrowness of the states was due to an angular momentum barrier between the colored quark clusters which inhibits decay, and the decoupling from pionic decay channels stemmed from an OZI suppression of decays that involve annihilation of the strange quarks.

Another possible interpretation is that these states, if they are confirmed, are ‘molecular’ states of strange particles. The $a_0/f_0(980)$ states are established examples [4] of states which find their most natural interpretation as molecular states, which means that their wavefunctions have large components of lightly bound $K\bar{K}$ mesons. The $\Lambda(1405)$ may have a similar structure. In the present case, we note that the $X$-state masses are suggestive of $K^*Y$ bound states, as shown in Table 1. The $K^*(892)$ has a width of 50 MeV, while the ‘binding energies’ of the $X$ states observed in Refs [1] [2] are in the range of a few tens of MeV. The states may be analogous to the $a_0/f_0(980)$ states or the $\Lambda(1405)$, with the interesting difference that one of the molecular partners, the $K^*$, is wide in mass compared to the effective width of the bound state. The $X$ molecular states could therefore decay directly to $K^* + Y$ through the “tails” of the mass distributions. Alternatively, the decays could involve more complicated quark rearrangements, would be correspondingly slower, and yield particles such as the observed kaons and Sigmas. These latter decays would be
analogous to the fate of the Λ(1405), which decays only to Σπ.

Photoproduction offers a way to confirm the existence of these states and to test the internal structure hypotheses. A photon in the GeV energy range can behave as a vector-dominance φ, so photoproduction is a natural possibility for injecting the right quark content into the nucleonic system in the s channel via the reaction γ+p → X → K+Y, as illustrated in Fig. II. The X states would appear as s-channel bumps, and would be straightforward to detect using a tagged bremsstrahlung beam and a suitable spectrometer, provided the s channel is dominant. In both the ‘exotic’ and the ‘molecular’ interpretations of these states, the line shapes for a given channel should be Breit-Wigner resonances modified due to the opening of the K∗Y channels. This is discussed in some detail below. The integrated branching fractions for KY versus K∗Y′ final states ought to be strong clues to the structure of these states. In principle, using photoproduction with good (∼5 MeV) energy resolution should make it possible to measure the line shapes directly.

II. PHOTOPRODUCTION DATA

The hidden-strangeness states introduced above would be produced as s channel resonances in photoproduction centered at photon energies, $E_\gamma$, of

$$X(2000) \rightarrow \Sigma^0 + K^+ \quad E_\gamma = 1700MeV$$

and

$$X(2050) \rightarrow \Sigma(1385) + K^+ \quad E_\gamma = 1750MeV$$

Bubble chamber experiments published in the late sixties [5] [6] provide us with a glimpse of strange particle photoproduction. They typically did not achieve enough resolution or statistics to make detailed analyses of isobar formation. They did have very good acceptance for all charged final states, and thus were able to broadly measure and categorize whole classes of reactions. The total strangeness photoproduction cross section from the Cambridge
Bubble Chamber Group shows a fairly dramatic increase, from 2 to 10 micro-barns, just below 2 GeV, as seen in Fig. 2. The increase cannot be explained as the sum of all available two-body channels, nor has it been studied in terms of more complex final states. Thus, no useful information can be gleaned for our present purpose from the total cross section.

In magnetic spectrometer experiments it should be possible to pick out strong s-channel resonances directly, simply by detecting a $K^+$ at any kinematically allowed fixed angle. Feller et al. used the bremsstrahlung difference method to detect $\gamma + p \rightarrow \Sigma^0 + K^+$ at approximately fixed $t$ (fixed spectrometer angle) at Bonn. Fig. 3 shows their data for $K^+$ production with a recoiling $\Sigma^0$. It is surprising and unfortunate that a data point at an energy corresponding to the mass of the $X(2000)$ is missing. The other data points give no hint of a 100 MeV wide structure in this region. Fortunately, an experiment by Göing et al. from DESY covered a similar range of $W$ (c.m. energy) at larger $t$. This was a bremsstrahlung experiment in which the photon endpoint was scanned over the range of interest, and results extracted from the excitation curves at a few fixed spectrometer momenta. Fig. 3 shows their results for $\Sigma^0$ production, which range up to just 2 GeV in mass, where the centroid of the $X(2000)$ state of should be. There is no sign of an s-channel resonance centered at 2 GeV with a 100 MeV width in these data. Both groups fit their data with phenomenological resonance models and obtained qualitative agreement with their data sets. Thus we can conclude that there is no support in the existing photoproduction data for the $X(2000)$. It would perhaps be interesting to obtain higher statistics samples of this kind of data to be certain.

Photoproduction of the $\Sigma(1385)$ has not been extracted from any spectrometer experiment. We are forced to reconsider the sparse bubble chamber data, which are collected in Fig. 4. The $\Sigma(1385)$ decays to $\Lambda\pi$ 88% of the time. Thus we consider the data for $\gamma + p \rightarrow K + \Lambda + \pi$ as a function of photon energy. In the CBCG study, the $\Lambda\pi$ invariant mass spectrum (not shown here) summed over all energies had a peak corresponding to $\Sigma(1385)$ production; it comprised about 26% of the $\Lambda + \pi + K$ final states. Thus, this final state had a significant component going through the particular two-body decay of interest.
here. Examining Fig. 4, we find a possible bump at roughly the right energy ($E_{\gamma} = 1.75$ \text{GeV}) to form the $X(2050)$. This bump amounts to no more that one high channel with a one-sigma error bar, but it is the only “high” channel in the spectrum. Note that the error bars in this plot look too large to be purely statistical. The number of raw counts in each bin of this histogram is not clear, but perhaps the significance of the peak is statistically greater than it appears from the error bars alone. In any event, this bump is the only hint of narrow $s$-channel structure in any of the final states from this CBCG measurement.

AbbHMM published a comparable spectrum from their experiment \cite{6}, as also shown in Fig. 4. In this case, the single specific final state was $K^0 + \Lambda + \pi^+$, hence the smaller cross section. Once again, the highest channel is near the photon energy corresponding to formation of an $X(2050)$, albeit with an enormous statistical uncertainty. Thus there are two photoproduction measurements containing a hint of a feature which could be related to a fairly narrow $s$-channel resonance near a mass of $2050$ \text{MeV}. It would be interesting, therefore, to accumulate some new data in this energy range of photoproduction to clarify this situation \cite{11}. If the high channels seen in the old experiments are related to an $X(2050)$, it is possible that a simple $s$-channel scan will reveal the state.

**III. LINESHAPES**

Henceforth we consider only an $X(2050)$ state. If it exists, and if it decays into both $K\Sigma(1385)$ and $K^*\Sigma^0$, it would clearly be valuable to measure the branching ratio for these final states. This information will be an important clue to the internal structure of the state. Because the state sits close to the $K^*\Sigma^0$ threshold, and may be a bound ‘molecule’ of these particles, measurement of the branching ratio may depend on knowledge of the distorted lineshapes in these two channels. These lineshapes can perhaps be measured in photoproduction experiments at, for example, Jefferson Lab, using a tagged photon beam and a kaon spectrometer. One can then ask, how strongly are the lineshapes distorted due to the proximity of the $K^*\Sigma^0$ threshold?
As a simple model calculation we consider the $X(2050)$ decaying to just the two channels mentioned above. We compute the lineshapes in these channels using the Flatté formula for a single resonance decaying to two final states, as discussed in Chung et al. [12]. The $X(2050)$ appears as a “normal” resonance in $K\Sigma(1385)$ (channel 1), and highly distorted in $K^*\Sigma^0$ (channel 2). The mass projection, $P(m)$, of channel 1 is related to a Lorentz invariant T-matrix element $\hat{T}_{11}(m)$, and a mass-dependent density of states $\rho_1(m)$, by

$$P(m) \propto |\rho_1(m)\hat{T}_{11}|^2$$

The T-matrix element for channel 1 is written as

$$\hat{T}_{11}(m) = \frac{\gamma_1^2 m_0 \Gamma_0}{m_0^2 - m^2 - im_0 \Gamma_0 (\rho_1(m) \gamma_1^2 + \rho_2(m) \gamma_2^2)}$$ (3.1)

with an analogous expression for $\hat{T}_{22}$ of channel 2. The ‘reduced’ widths for the two channels, denoted $\gamma_1^2$ and $\gamma_2^2$, satisfy $\gamma_1^2 + \gamma_2^2 = 1$. The parameters $m_0$ and $\Gamma_0$ are the mass and width one would estimate if channel 1 were due to decay of a single isolated resonance. The observed mass, $m_X$, and the observed (though perhaps distorted) width, $\Gamma_X$, seen in channel 1 are related to $m_0$ and $\Gamma_0$ by

$$m_0^2 = m_X^2 + m_X \Gamma_X \frac{\rho_2(m_X) \gamma_2^2}{\rho_1(m_X) \gamma_1^2}$$ (3.2)

and

$$\Gamma_0 = \Gamma_X \frac{m_X}{m_0} \frac{1}{\rho_1(m_X) \gamma_1^2} \frac{1}{\gamma_2^2}.$$ (3.3)

The density of states factors $\rho_1$ and $\rho_2$ are related to the available center-of-mass momentum, $q$, when a state of mass $m$ decays to two final states masses $m_a$ and $m_b$. The standard form [12] when $m_a$ and $m_b$ have negligible widths is $\rho(m, m_a, m_b) = 2q(m, m_a, m_b)/m$, which approaches unity as $m \to \infty$ and vanishes below the mass threshold. If either $m_a$ or $m_b$ are in turn states of finite width, such as the $K^*$ or $\Sigma(1385)$, then the density of available states rises with mass more gradually than an abrupt threshold. For the present model calculation we folded $\rho(m, m_a, m_b)$ with an s-wave Breit-Wigner lineshape $P_i(m_i), i = a, b,$ for the “broad” final state particle. For the density of states in channel 2 we used

$$\rho_2(m) = \int_0^{m-m_{\Sigma^0}} \rho(m, m_{K^*}, m_{\Sigma^0})P_{K^*}(m_{K^*})dm_{K^*}.$$ (3.4)
The convolved form for $\rho_2$ is intended to account for the width of the $K^*$ final state, and the fact that not all of the phase space for channel 2 is available at a given value of the mass of the state $m_X$. $P_{K^*}(m_{K^*})$ is a simple Breit-Wigner lineshape for the $K^*$.

In Fig. 5, the results of this calculation are shown for a series of possible widths observed in channel 1, the ‘normal’ resonance channel. The ratio of reduced widths, $\gamma_1^2/\gamma_2^2$, was set equal to unity because the lineshapes were found to be not drastically sensitive to this ratio for values above 0.1. The main sensitivity of the lineshape was seen in the dependence on width, $\Gamma_X$, in the $K^*\Sigma^o$ case. The solid lines are for $\Gamma_X = 35\text{MeV}$, the nominal observed width reported in the experiment [1]. For this width, the second channel is predicted to have a broad structure with a second maximum in the mass. The shape of the $K^*(892)\Sigma^o$ distribution varies rapidly as the observed width of the $K\Sigma(1385)$ channel is varied from 20 to 100 MeV. On the other hand, the shape of the $K\Sigma(1385)$ channel is rather insensitive to the opening of the $K^*\Sigma^o$ channel. Thus, careful measurement of the $K^*\Sigma^o$ final state lineshape would help define the $X(2050)$ width. No strong variations in lineshape was found when the position of the mass centroid was varied over the roughly 20 MeV range of experimental uncertainty.

From this study it may be concluded that careful measurements of the lineshapes of the $X(2050)$, if it exists, would not be sensitive to the ratio of reduced widths. However, the $K^*(892)\Sigma^o$ final state is quite sensitive to the precise width of the $X(2050)$.

**IV. CONCLUSIONS**

We have shown that strangeness photoproduction data off the proton covering the $s$-channel mass range around 2000 MeV do not confirm a 100 MeV wide state seen at this mass in coherent diffractive proton scattering [1]. On the other hand, strangeness photoproduction data near a mass of 2050 MeV mildly supports the existence of another state seen in the same proton scattering experiment. If confirmed by new and better experiments in photoproduction, either of these states may be of considerable interest as exotic “hidden
strangeness” states, since their decays are dominantly to strange particles. A computation of the distorted lineshapes of the \(X(2050)\) state shows that it will appear nearly as a normal resonance in the \(K\Sigma(1385)\) channel, and strongly distorted in the \(K^*(892)\Sigma^0\) channel. Experiments at the new generation of photon facilities should make such experiments feasible; initial experiments would be straightforward ‘single-arm’ kaon measurements using a tagged photon beam.

ACKNOWLEDGMENTS

I thank Zhen-Ping Li and Curtis Meyer for helpful discussions, as well as L.G. Landsberg for discussions of the data. This work was supported by DOE contract DE-FG02-87ER40315.
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FIGURES

FIG. 1. $s$-channel photoproduction of strangeness-rich intermediate states via vector dominance $\phi$'s.

FIG. 2. Total cross section for strange particle photoproduction. The data are from Ref. [5].

FIG. 3. Exclusive strangeness photoproduction of the $\Sigma^0$. Data are from Refs. [8] and [9], and include points from other experiments. Location expected for $s$-channel production of an $X(2000)$ with a width of 99 MeV is indicated by the arrow and the dashed lines.

FIG. 4. Total cross sections for all charge combinations for $\gamma + p \rightarrow \{\Lambda, \Sigma\} + K + \pi$ from Ref. [10] and for $\Lambda + K^0 + \pi^+$ from Ref. [6]. Location expected for $s$-channel production of an $X(2050)$ with a width of 35 MeV is indicated by the arrow and the dashed lines.

FIG. 5. Predicted lineshapes of the $X(2050)$ decaying to two final states for equal reduced widths $\gamma_i^2$. The observed FWHMs of the $X(2050)$ are the nominal 35 MeV (solid lines), 20 MeV (short dash), 50 MeV (dotted), and 100 MeV (dot-dash). In each case the curves are arbitrarily normalized.
TABLES

TABLE I. Mass comparisons of ‘narrow’ states with ‘molecular’ combinations of known mesons and baryons.

| ‘Molecular’ Structure | Constituent Mass Sum (MeV) | Observed State | ‘Binding Energy’ (MeV) |
|-----------------------|---------------------------|----------------|------------------------|
| $K^+K^-$              | 988                       | $a_0/f_0(980)$ | 8                      |
| $KN$                  | 1435                      | $\Lambda(1405)$ | 27                     |
| $K^*(892)\Lambda$     | 2007                      | $X(2000)$      | 10                     |
| $K^*(892)\Sigma^0$    | 2084                      | $X(2050)$      | 35                     |
Strangeness Photoproduction

CBCG: $\gamma + p \rightarrow$ strange particles

TOTAL CROSS SECTION (\(\mu b\))

PHOTON ENERGY (GeV)

AK Threshold
\[ \gamma + p \rightarrow K^+ + \Sigma^0 \]

- **Feller et al.**: $25^\circ < \theta_{k}^{\text{c.m.}} < 32^\circ$
- **Going et al.**: $\theta_{k}^{\text{c.m.}} = 90^\circ$

The graph shows the dependence of the differential cross section $d\sigma/d\Omega$ (in nb/sr) on the photon energy in GeV.
Strangeness Photoproduction

- CBCG: $\gamma + p \rightarrow \Lambda + K + \pi$ and $\Sigma + K + \pi$
- ABBHHM: $\gamma + p \rightarrow \Lambda + K^0 + \pi^+$

CROSS SECTION ($\mu$b) vs. PHOTON ENERGY (GeV)
