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The study of unconventional baryon structure in the light quark sector with the BGOOD photoproduction experiment

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The BGOOD photoproduction experiment accesses forward meson angles and low momentum exchange kinematics in the *uds* sector, which may be sensitive to molecular-like hadron structure.

Our results in the strangeness sector suggest a dominant role of meson-baryon dynamics. This includes structures in $K^0\Sigma^0$, $K^+\Sigma^0$ and $K^+\Sigma^0(1385)$ residing at $\Sigma^{(*)}K^{(*)}$ thresholds which have an equivalence of the P_C states at the $\Sigma_C^{(*)}\bar{D}^{(*)}$ thresholds.

In the non-strange baryon-baryon sector, forward differential cross section measurements of coherent meson photoproduction off the deuteron are orders of magnitude higher than model calculations and what would be anticipated due to the large momentum transferred to the deuteron. The origin of these enhancements, for example intermediate dibaryon formation or final state interactions of pion re-scattering is still under debate.

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1. Introduction

Exotic, multi-quark states beyond valence three-quark and quark-antiquark systems are now unambiguously realised in the heavy, charmed quark sector. Many of these states, such as the P_c pentaquarks [1] and XYZ mesons [2] reside close to open charm thresholds, indicative of molecular-like structure. Equivalent structures may also be evidenced in the light, *uds* sector, including the $\Lambda(1405)$ and a cusp-like structure in $K^0\Sigma^+$ photoproduction at the $K^*\Sigma$ threshold [3, 4].

Experimentally, access to a low momentum exchange region is mandatory to elucidate the role of molecular-like structure (if they are loosely bound and spatially extended systems) in reaction mechanisms. In a photoproduction experiment with a fixed target, this corresponds to forward meson acceptance to ensure the recoiling hadron system has minimal momentum transfer. The BGOOD experiment [5] at the ELSA electron accelerator facility [6] is ideally suited for this. A 3 GeV electron beam impinges upon a thin radiator to produce an energy tagged bremsstrahlung photon beam which is subsequently incident upon a liquid hydrogen or deuterium target. BGOOD is comprised of two main parts, a central calorimeter region ideal for the reconstruction of neutral mesons via their decays, and a forward spectrometer used for charged particle identification and momentum reconstruction at forward angles.

2. Strangeness photoproduction at BGOOD

2.1 The $\gamma n \to K^0\Sigma^0$ differential cross section over the K^* threshold

The coupled channel model in Ref. [4] purported a dynamically generated $N^*(2030)$ as the origin of a cusp measured in $K^0\Sigma^+$ photoproduction [3], which was also predicted to cause a peak-like structure in $K^0\Sigma^0$. Observing this would therefore provide evidence of a molecular state in the *uds* sector. An example of the differential cross section measured at BGOOD is shown in Fig. 1 [7]. The data are in reasonable agreement with the previous data from the A2 collaboration [14] and in the more forward interval shown, are consistent with the predicted peak from Ref. [4].[1] Further data has now been taken to enable a firm interpretation.

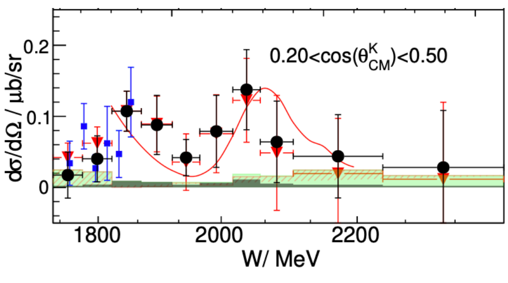

Figure 1: $\gamma n \to K^0\Sigma^0$ differential cross section for $0.2 < \cos\theta^K_{CM} < 0.5$, employing two different fitting methods for yield extraction (red triangles and black circles). The blue squares are data from the A2 Collaboration [14]. The predicted total cross section from Ref. [4] is shown as the red line at an arbitrary scale. Figure adapted from Ref. [7].

2.2 Photoproduction of $K^+\Lambda(1405) \to K^+\pi^0\Sigma^0$

Reference [15] proposes that a triangle singularity contributes to $K^+\Lambda(1405)$ photoproduction, resulting in an enhancement at $W \sim 1900$ MeV. This singularity is driven by the same dynamically generated $N^*(2030)$ predicted in Ref. [4] for $K\Sigma$ photoproduction. This would support the

[1] The model calculation however is the integrated cross section over all $\cos\theta^K_{CM}$ and set at an arbitrary scale. A differential cross section calculation would be highly desirable for an accurate comparison.

molecular-like structure of the $N^*(2030)$ as it must reside close to the $K^*\Sigma$ threshold and have a strong coupling to the open-strange system. Figure 2 shows the cross section measured at BGOOD. The purple line is the model calculation in Ref. [15] of the triangle singularity being driven by the $N^*(2030)$ resonance, with excellent agreement to the BGOOD data.

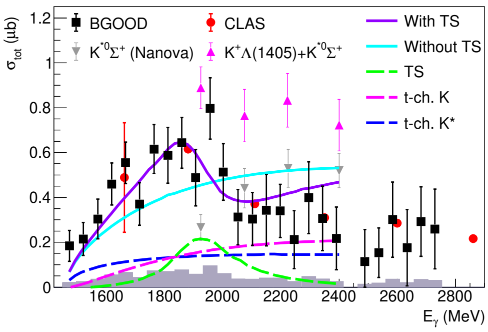

Figure 2: The integrated $\gamma p \to K^+\Lambda(1405)$ cross section [8] (black squares). The purple and cyan line is the model from Ref. [15] with and without the triangle singularity, the $K^{*0}\Sigma^+$ data from CBELSA/TAPS are the grey triangles and the sum of the $K^{*0}\Sigma^+$ and the BGOOD $K^+\Lambda(1405)$ data are the magenta triangles. Red circles are CLAS data. Figure and references from Ref. [8].

2.3 K^+Y photoproduction at forward angles and low momentum transfer

Shown in Fig. 3, $K^+\Lambda$, $K^+\Sigma^0$, $K^+\Sigma^-$ (preliminary), $K^+\Lambda(1520)$ and $K^+\Sigma(1385)$ (preliminary) differential cross sections for $\cos\theta^K_{\mathrm{CM}} > 0.9$ have been measured at BGOOD with high statistical precision [9–13].

The $K^+\Sigma^0$ differential cross section exhibits a cusp-like structure close to the pK^+K^- threshold at $W \sim 1900$ MeV (Fig. 3(b)). This becomes most pronounced at minimum momentum transfer, t_{min} and $\cos\theta^K_{\mathrm{CM}} = 1$ (Fig. 3(c)) where it could be regarded as a peak at the $\Sigma(1385)K^+$ threshold. Fitting a Breit-Wigner function to this peak with a polynomial to describe the trend of the data yields a mass and width consistent with the summed $K\Sigma(1385)$ mass and a width of the $\Sigma(1385)$. Numerous model calculations (see for example Ref. [16] and references therein) predict equivalent P_C states in the strangeness sector, where if proven correct, a molecular $\Sigma^0(1385)K^+$ system would be the strange analogue of the $P_C(4382)$ which resides at the $\Sigma^*_C\bar{D}$ threshold. This is supported by the $K^+\Sigma^0(1385)$ differential cross section which was measured from threshold for the first time (Fig. 3(f)). A prominent peak is also observed, which is qualitatively described by a simple toy model of ρ exchange between the K^+ and $\Sigma(1385)$ at relative low momentum (the green line). It is interesting to note the results of Ref. [17], where a coupled-channel approach was used to describe the P_C states as $\Sigma^{(*)}_C\bar{D}^{(*)}$ molecules. Line shapes for $\Sigma^{(*)}_C\bar{D}^{(*)}$ final states above threshold were determined to have a dependence on P_C formation, resulting in peak-like structures which appear very similar to what is observed in $K^+\Sigma(1385)$ photoproduction. A speculative comparison between the P_C states residing at $\Sigma^{(*)}_C\bar{D}^{(*)}$ thresholds and pentaquark candidates in the strangeness sector at $\Sigma^{(*)}K^{(*)}$ is made in Table 1.

3. Coherent meson photoproduction off the deuteron at BGOOD

Shown in Fig. 4, differential cross sections for the coherent reactions, $\gamma d \to \pi^0\pi^0 d$ [20], $\gamma d \to \pi^0\eta d$ [21] and $\gamma d \to \pi^0\pi^0\pi^0 d$ (preliminary) [22] have been made with BGOOD where the deuteron is identified in the forward spectrometer (corresponding to $\cos\theta^d_{\mathrm{CM}} > 0.8$). All of the differential cross sections are unexpectedly large. The three-momentum transfer to the deuteron

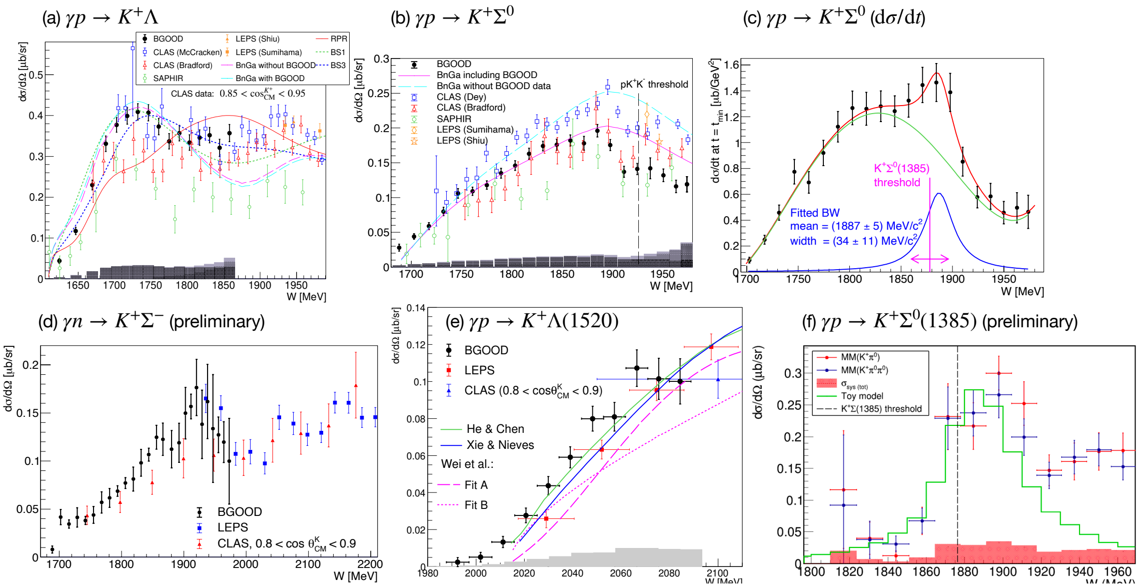

Figure 3: Forward differential cross sections for (a) $K^+\Lambda$ [9], (b,c) $K^+\Sigma^0$ [10], (d) $K^+\Sigma^-$ [11], (e) $K^+\Lambda(1520)$ [12] and (f) $K^+\Sigma^0(1385)$ [13]. All data correspond to $\cos\theta^K_{\mathrm{CM}} > 0.9$ except (c) which is differential with respect to t at minimum t (corresponding to $\cos\theta^K_{\mathrm{CM}} = 1$).

J^P	Charm sector		Strange sector	
	Threshold	State	Threshold	Evidence
$\frac{1}{2}^-$	$\Sigma_c\bar{D}$	$P_c(4312)$	Σ^0K^+	$N(1535)$ (see for example Ref. [18])
$\frac{3}{2}^-$	$\Sigma_c^*\bar{D}$	$P_c(4382)$	$\Sigma^0(1385)K^+$	Peak in $K^+\Sigma^0$ [10]
$\frac{3}{2}^-$	$\Sigma_c\bar{D}^*$	$P_c(4457)$	Σ^0K^{*+}	Peak in $K^0\Sigma^0$ [7], Cusp in $K^0\Sigma^+$ [3], Triangle singularity in $K^+\Lambda(1405)$ [8]

Table 1: Comparison between P_c states and their proximity to thresholds to $K\Sigma$ thresholds and evidence of molecular states. The $P_c(4382)$ is a suggestion from Du *et al.* [19].

ranges between 0.4 and 1.0 GeV/c respectively, which is much higher than the Fermi momentum of the constituent nucleons (typically 80 MeV/c) and therefore what can be transferred to the deuteron for it to remain intact. This is demonstrated in the model calculations in Refs. [23, 24] for $\pi^0\pi^0 d$, which is an order of magnitude smaller at forward angles due to the increasing momentum transfer.

The origin of the unexpectedly large cross sections is not yet clear. One suggestion could be the formation of intermediate dibaryons, for example the $d^*(2380)$ [25, 26], however it is not conclusive. Alternatively, there may be large contributions from final state interactions, for example the diagrams shown in Fig. 5 (left panel). To test this hypothesis, a toy model of the two diagrams was made, assuming on-shell kinematics, which gives an excellent description of the data. Detailed quantitative model calculations, for example the model of Egorov and Fix [24] however suggest that final state interactions contribute only a few percent of the measured cross section (magenta line in Fig. 5).

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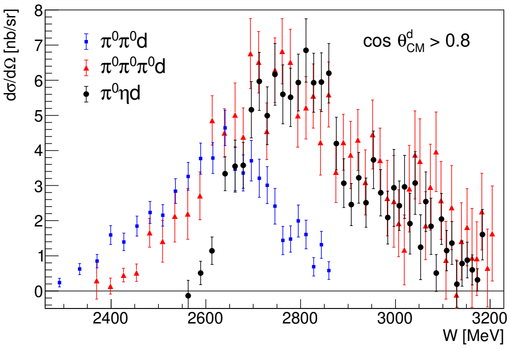

Figure 4: Coherent meson photoproduction off the deuteron for $\cos\theta^d_{\mathrm{CM}} > 0.8$ measured at BGOOD [20–22].

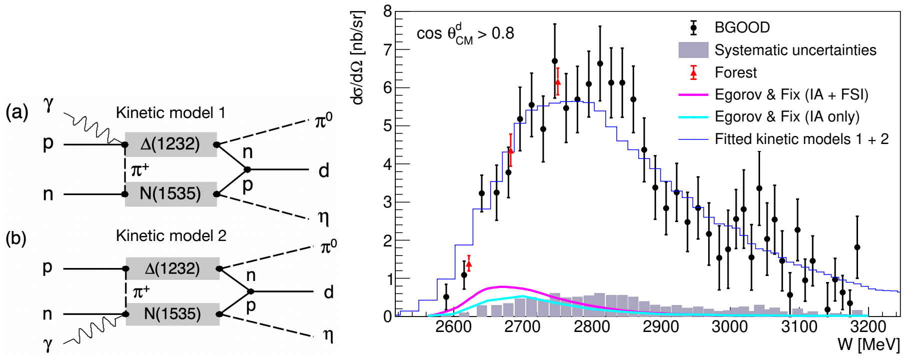

Figure 5: Left: Proposed final state interactions contributing to $\gamma d \to \pi^0 \eta d$. Right: Coherent $\pi^0\eta d$ photoproduction off the deuteron for $\cos\theta^d_{\mathrm{CM}} > 0.8$ measured at BGOOD (black circles with systematic errors as filled grey bars on the abscissa). Previous data from the FOREST detector [27], the model calculation of Egorov and Fix using an impulse approximation (IA) and with additional final state interactions (FSI) [24] and the toy model based upon diagrams *kinetic model* 1 and 2 (left) are indicated labelled in the legend. Figure adapted from Ref. [21].

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