The BGOOD experiment at ELSA, exotic structures in the light quark sector?

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Abstract. 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. Recent results are presented, including strangeness photoproduction at forward meson angles, and $\pi^0\pi^0$ coherent photoproduction off the deuteron.

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] which was suggested to derive from a vector meson-baryon dynamically generated state, the $N^*(2030)$ [4]. Experimentally, access to a low momentum exchange region is mandatory to elucidate the role of such states 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 [6] at the ELSA electron accelerator facility [7] 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 the target at the centre of the BGOOD experiment. BGOOD

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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.

The physics programme at BGOOD is currently focussed on two areas: strangeness photoproduction, with an emphasis on the role of exotic candidates in the reaction mechanism (Sec. 2), and coherent meson photoproduction of the deuteron at forward angles (Sec. 3).

2 Strangeness photoproduction at BGOOD

BGOOD has an extensive strangeness photoproduction physics programme [8–11], with an emphasise on studying reactions at low momentum transfer (low t). Recent results are highlighted in this section.

2.1 The $\gamma n \rightarrow K^0\Sigma^0$ differential cross section over the K^* threshold [8]

A model by Ramos and Oset suggested a dynamically generated $N^*(2030)$ is the origin of a cusp measured in the $K^0\Sigma^+$ channel [3, 4]. The model also predicted constructive interference in $K^0\Sigma^0$ photoproduction resulting in a peak. Observing this experimentally would therefore be direct evidence of a molecular state in the uds sector.

An example of the differential cross section measured at BGOOD is shown in Fig. 1. The data are in reasonable agreement with the previous data from the A2 collaboration [12] and in the more forward interval shown, are consistent with the predicted peak from the model of Ramos and Oset.[1] Further data has now been taken to improve the statistical precision and enable a firm interpretation.

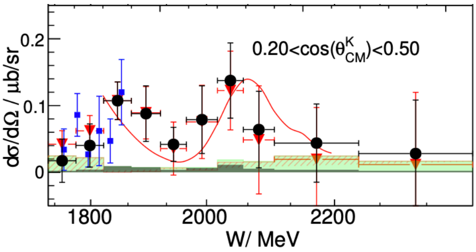

Figure 1. $\gamma n \rightarrow K^0\Sigma^0$ differential cross section for $0.2 < \cos\theta^K_{\mathrm{CM}} < 0.5$ and two different fitting methods (red triangles and black circles). The blue squares are data from the A2 Collaboration [12]. The predicted total cross section from Ramos and Oset [4] is included at an arbitrary scale. Figure adapted from Ref. [8].

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2.2 Photoproduction of $K^+\Lambda(1405) \rightarrow K^+\pi^0\Sigma^0$ [9]

Shown in Fig. 2 (left), Ref. [13] proposes that a triangle singularity contributes to the $K^+\Lambda(1405)$ photoproduction, where the “legs" of the triangle are almost on shell, resulting in an enhancement at a centre-of-mass energy of 1900 MeV. This singularity is driven by the same dynamically generated $N^*(2030)$ resonance suggested in $K\Sigma$ photoproduction. The width of this enhancement has a dependence upon both the width of $N^*(2030)$ and the intermediate K^*. If this is proven to be correct, the mechanism supports the 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.

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

Figure 2 (right) shows the cross section versus photon beam energy measured at BGOOD, integrated over all $\cos\theta^K_{\mathrm{CM}}$, with good agreement to previous CLAS data and with improved beam energy resolution. The purple line is the calculation by Wang *et al.* of the triangle singularity being driven by the $N^*(2030)$ resonance [13]. The calculation was made only up to $W = 2.4$ GeV, covering the region affected by the triangle singularity. The excellent agreement supports the description of a molecular-like $N^*(2030)$ driving a triangle singularity.

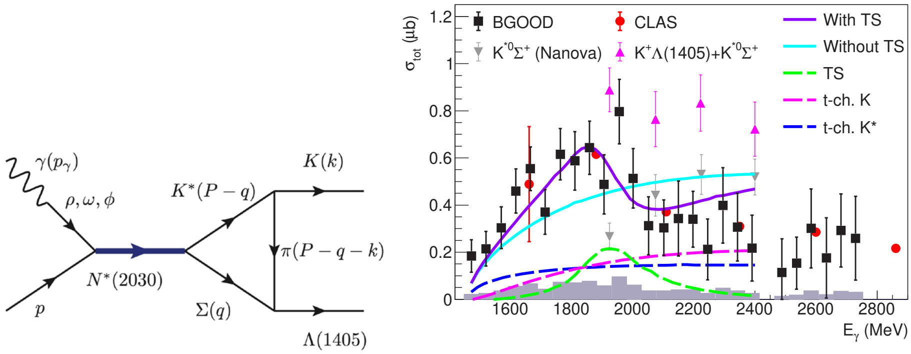

Figure 2. Left: The triangle singularity proposed to contribute to $K^+\Lambda(1405)$ photoproduction. Figure from Ref. [13]. Right: The integrated $\gamma p \to K^+\Lambda(1405)$ cross section. The purple and cyan line is the model of Wang *et al.* [13] with and without the triangle singularity, the $K^{*0}\Sigma^+$ 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 of other datasets are in Ref. [9].

2.3 $K^+\Sigma^0$ photoproduction at forward angles and low momentum transfer [10, 11]

$K^+\Lambda$ and $K^+\Sigma^0$ differential cross sections for $\cos\theta^K_{\mathrm{CM}} > 0.9$ have both been measured at BGOOD with high statistical precision [10, 11]. The $K^+\Sigma^0$ differential cross section is shown in Fig. 3 (left). A cusp-like structure is resolved close to the pK^+K^- threshold at $W \sim 1900$ MeV. Figure 3 (right) shows the data extrapolated to minimum momentum transfer, t_{min} and $\cos\theta^K_{\mathrm{CM}} = 1$, where the cross section drops by 75 %. The extent of this cusp-like structure changes quickly over $\cos\theta^K_{\mathrm{CM}}$ at forward angles, demonstrating the importance of accessing these forward kinematics.

It is speculated that there appears an equivalence of exotic state candidates observed in these strangeness photoproduction data compared to the P_c states. As outlined in the introduction, the proximity of the states to open charm (see for example the description in Ref. [22]), or in this case strange thresholds supports a molecular description. The cusp in the $K^+\Sigma^0$ differential cross section shown in Fig. 3 (right) could be regarded as a peak exactly at the $\Sigma(1385)K^+$ threshold. This, and other suggested candidates are compared to the P_c states in table 1.

3 Coherent photoproduction off the deuteron at BGOOD [14]

A renaissance in the search for dibaryon states began with the discovery/confirmation of the $d^*(2380)$ in the isoscalar ($I = 0$) channel [15, 16]. The $d^*(2380)$ may have first been observed indirectly earlier in the 1960s via low mass enhancements in $\pi\pi$ invariant mass spectra [17]

J^P	Charm sector		Strange sector	
	Threshold	State	Threshold	Evidence
$\frac{1}{2}^-$	$\Sigma_c \bar{D}$	$P_c(4312)$	$\Sigma^0 K^+$	$N(1535)$
$\frac{3}{2}^-$	$\Sigma_c^* \bar{D}$	$P_c(4382)$	$\Sigma^0(1385)K^+$	Peak in $K^+\Sigma^0$ [11]
$\frac{3}{2}^-$	$\Sigma_c \bar{D}^*$	$P_c(4457)$	$\Sigma^0 K^{*+}$	Peak in $K^0\Sigma^0$ [8], Cusp in $K^0\Sigma^+$ [3], Triangle singularity in $K^+\Lambda(1405)$ [9]

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.* [22].

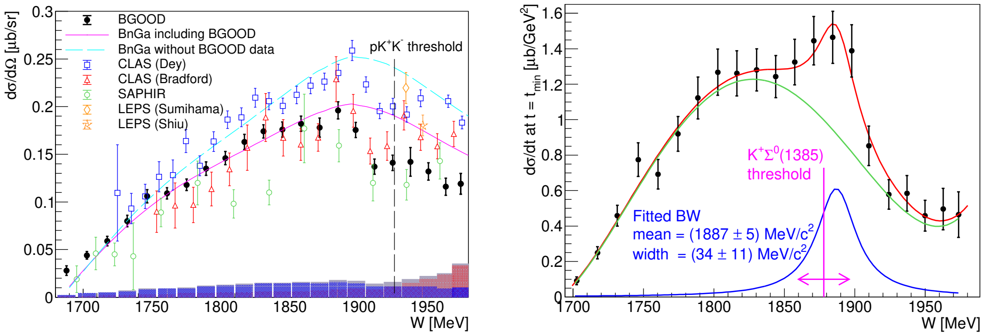

Figure 3. Left panel: $\gamma p \rightarrow K^+\Sigma^0$ differential cross section for $\cos\theta^K_{\mathrm{CM}} > 0.90$ (black circles). The systematic uncertainties on the abscissa are in three components, where the grey bars are the total. Previous data (only including statistical errors) and model calculations are indicated in the legend. The CLAS data are at the more backward angle of $0.85 < \cos\theta^K_{CM} < 0.95$. Right panel: $\mathrm{d}\sigma/\mathrm{d}t$ extrapolated to t_{min} versus W. The data is fitted with a third order polynomial (green line) summed with a Breit-Wigner function (blue line). The $K^+\Sigma(1385)$ threshold is indicated in magenta, with the $\Sigma(1385)$ width indicated by the arrow. Figures and references from Ref. [11].

from deuteron formation in pn reactions, which was also evidenced recently by the WASA collaboration [16].

The reaction $\gamma d \rightarrow \pi^0\pi^0 d$ is an ideal channel to search for dibaryons as the isoscalar final state is only sensitive to intermediate isoscalar dibaryons, compared to $\gamma d \rightarrow \pi^+\pi^- d$ which also has isovector coupling and background contributions from the large $\gamma N \pi^\pm$ coupling. The reaction was identified at BGOOD via the two $\pi^0 \rightarrow \gamma\gamma$ in the BGO Rugby Ball and the deuteron identified in the Forward Spectrometer. The differential cross section for $\cos\theta^d_{\mathrm{CM}} > 0.8$ is shown in Fig. 4. The data peaks at $W \sim 2650$ MeV with a magnitude of 4 nb/sr. This is approximately an order of magnitude higher than the model prediction of Fix, Arenhövel and Egorov [18, 19] (shown as comparison in Ref. [14]) which assumed coherent production off the deuteron, where at forward angles the differential cross section falls very quickly due to the increasing momentum transfer. At $W = 2300$ and 2800 MeV, the three-momentum transfer to the deuteron is 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.

The differential cross section data were fitted with the $d^*(2380)$ and the two additional isoscalar dibaryons reported by the ELPH collaboration [20]. A Breit-Wigner function is assumed for each dibaryon candidate, with masses and widths fixed from Ref. [20] but not

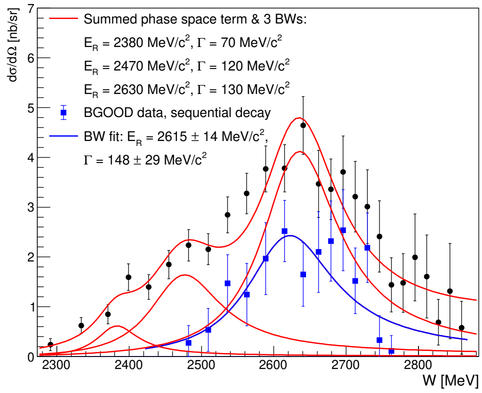

Figure 4. $\gamma d \to \pi^0\pi^0 d$ differential cross section for $\cos\theta^d_{\mathrm{CM}} > 0.8$ (black circles, statistical and systematic errors summed quadratically). A fit including three Breit-Wigner functions (BW) are shown as the red lines, with the fixed masses and widths labelled inset. The blue square data points are the differential cross section for the first of the sequential dibaryon candidate determined from the $\pi^0 d$ invariant mass distributions (an example of which is shown in fig. 5(b)) with a Breit-Wigner function fitted and the mass and width labelled inset. Figure from Ref. [14].

their relative amplitudes. A reduced χ^2 of 0.96 was achieved, demonstrating a consistency of the data with this three dibaryon scenario, however with limited statistical precision and resolution in W.

Figure 5(a) shows the invariant mass of the $\pi^0\pi^0$ system for a W range over the $d^*(2380)$. The low mass enhancement and a dip at approximately 0.34 GeV/c^2 appears similar to the ABC effect in Refs. [15, 16] which was attributed to the $d^*(2380)$. The pink line (scaled to match the data at 0.29 GeV/c^2) shows the expected distribution, where an intermediate $d^*(2380)$ is formed [21]. Qualitatively there appears a good agreement over the low mass range below 0.35 GeV/c^2, despite limited statistical precision. A fit was made to the data including this "ABC spectrum" and a differential cross section for $\gamma d \to d^*(2380) \to \pi^0\pi^0 d$ was determined as $(17 \pm 7_{\mathrm{stat}} \pm 4_{\mathrm{sys}})$ nb/sr.

Figure 5(b) shows the invariant mass of the $\pi^0 d$ system for $W = 2641$ - 2696 MeV. A double peaking structure is observed which is similar to what was observed by the ELPH Collaboration [20], where it was interpreted as an isovector dibaryon with a mass of 2140 ± 11 MeV/c^2 and a width of 91 ± 11 MeV/c^2 from the decay of an isoscalar dibaryon. This reaction mechanism was input to the BGOOD simulation where the mass and width was varied to achieve a minimal χ^2. Shown as the blue line with an additional phase space contribution in green, a mass of 2117 MeV/c^2 and a width of 20 MeV/c^2 proved optimal. The higher energy broader peak is the reflection of the uncorrelated $\pi^0 d$ combination. The measured width is approximately the same as the experimental resolution and can therefore be considered an upper limit. This is much narrower than the width of 91 MeV/c^2 reported by the ELPH collaboration, which cannot be accounted for in this data and cannot give a satisfactory fit.

The $\pi^0 d$ invariant mass for each W interval was fitted to extract the differential cross section of the proposed sequential decay shown as the blue squares in Fig. 4. A Breit-Wigner function was fitted, and both the mass and width agrees with the proposed highest mass dibaryon from the ELPH collaboration. It is therefore suggested that two decay modes of an $N\Delta$ isoscalar dibaryon are observed, either directly to $\pi^0\pi^0 d$ or to $\pi^0\mathcal{D}_{12}$, where the $\mathcal{D}_{12}$ is an $N\Delta$ configuration dibaryon. Alternative explanations however can not be excluded at present, such as pion re-scattering mechanisms and may yet explain the observed spectra without the need for intermediate dibaryons. In particular, it is hard to reconcile the narrow width of the proposed $\mathcal{D}_{12}$ given the numerous open strong decays available.

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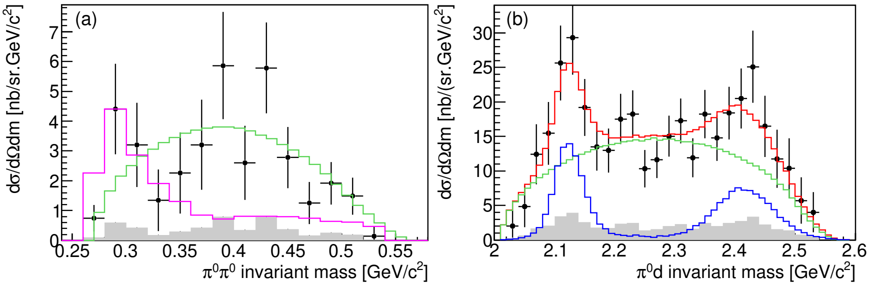

Figure 5. (a) The invariant mass of the $\pi^0\pi^0$ system for W from 2270 to 2441 MeV and $\cos\theta^d_{\mathrm{CM}} > 0.8$. The systematic uncertainties are the grey bars on the absisca. The green line is the phase space distribution with an integral equal to the measured data and the magenta line is the ABC effect distribution [21] with a scale fixed by the second data point at 0.29 GeV/c^2 (not the fit described in the text). (b) The invariant mass of the $\pi^0 d$ system for W from 2641 to 2696 MeV and $\cos\theta^d_{\mathrm{CM}} > 0.8$. The fitted distribution (red line) is comprised of phase space (green line) and the proposed sequential dibaryon decay (blue line). Figure adapted from Ref. [14].

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