Strangeness Photoproduction at the BGO-OD Experiment

T. C. Judea, *, S. Alefa, P. Baurea, R. Beckb, P. Colea, R. Di Salvoa, D. Elsnera, A. Fantinici,–d, O. Freyermuthb, F. Ghioe,–f, A. Gridnewa, D. Hammanna, J. Hannappela, K. Kohla, N. Kozenkoa, A. Lapika, P. Levi Sandrii, V. Lisina, G. Mandaglioj,–k, R. Messic,–d, D. Moriccianiv, V. Nedorezovb, D. Novinskiyf, P. Pedroni,–k, A. Polonisk, B. Reitza, M. Romaniukc, G. Scheluchincl, H. Schmiedena, V. Sumachevg, V. Tarakanovg, and C. Tillmannsa

a Physikalisches Institut, Universität Bonn, Nussallee 12, Bonn, D-53115 Germany
b Helmholtz-Institut für Strahlen- und Kernphysik, Universität Bonn, Nussallee 1-16, Bonn D-53115 Germany
c INFN Roma Tor Vergata, Via della Ricerca Scientifica 1, Rome, 00133 Italy
d INFN Roma Tor Vergata, Via della Ricerca Scientifica 1, Rome, 00133 Italy
e INFN sezione di Roma La Sapienza, P.le Aldo Moro 2, Rome, 00185 Italy
f Istituto Superiore di Sanità, Viale Regina Elena 299, Rome, 00161 Italy
g Petersburg Nuclear Physics Institute, Gatchina, Leningrad District, 188300 Russia
h Institute for Nuclear Research RAS, Moscow, 117312 Russia
i INFN—Laboratori Nazionali di Frascati, Via E. Fermi 40, Frascati, 00044 Italy
j INFN sezione Catania, Catania, 95129 Italy
k Universita degli Studi di Messina, Via Consolato del Mare 41, Messina, 98121 Italy
l INFN sezione di Pavia, Via Agostino Bassi, 6, Pavia, 27100 Italy

* e-mail: jude@physik.uni-bonn.de

Received March 4, 2019; revised March 20, 2019; accepted March 29, 2019

Abstract—The BGO-OD experiment at the ELSA accelerator facility uses an energy tagged bremsstrahlung photon beam to investigate the excitation structure of the nucleon. The setup consists of a highly segmented BGO calorimeter surrounding the target, with a particle tracking magnetic spectrometer at forward angles. BGO-OD is ideal for investigating low momentum transfer processes due to the acceptance and high momentum resolution at forward angles. In particular, this enables the investigation of strangeness photoproduction where t-channel exchange mechanisms play an important role. This also allows access to a kinematic region where extended, molecular structure may manifest in reaction mechanisms. The extensive strangeness photoproduction programme includes the photoproduction of neutral and charged kaons using both hydrogen and deuterium targets.

DOI: 10.1134/S1063779619050113

1. INTRODUCTION

Hadron spectroscopy has for many years been used to determine the interactions between the partons of the nucleon, and the degrees of freedom afforded in non-perturbative QCD. Despite the wealth of data for both the pion and photoproduction of many hadronic states, there remain many “missing resonances” which are predicted by Constituent Quark Models (CQM) but are not observed experimentally [1]. Moreover, some of the lowest observed states are not described satisfactorily. The pattern of the mass and parity of the Roper resonance (N (1440) 1/2 +) and the N (1535) 1/2 – for example, where the state above ground state would be expected to have negative parity, is hard to reconcile with a CQM of “dressed” quarks in a mutually generated potential, irrespective of the shape of this potential. The Λ (1405) — Λ*(1535) mass ordering (despite the Λ (1405) being a uds singlet state), and the mass between the Λ (1405) and its spin-orbit partner, Λ (1520), are also difficult to interpret within a CQM framework.

In the charmed quark sector, the pentaquark states, Pc (4450) + and Pc (4380) + [2] are one of the first indications of baryons of at least five constituent quarks. Since the conception of the quark model, there has been discussion of the possibility of hadrons of more than three constituent quarks [3–5], and due to the proximity of the chiral symmetry breaking scale to the nucleon mass, it is possible that light mesons may interact as elementary objects, giving rise to molecular systems and meson rescattering effects near thresholds [6, 7]. It is still an open question whether the pentaquark states are bound five quark systems, or have a molecular–like composition to some extent. The
model of Wu et al. [8], for example, successfully describes these as meson–baryon dynamically generated states. Similarly in the meson sector, the $X(3872)$ lies close to the $D^0\bar{D}^{*0}$ threshold and has also been described as a molecular state (see for example [9]).

In the “light” strange quark sector, models including molecular-like meson-baryon interactions as additional degrees of freedom have had improved success in describing observed states [10–14]. The $\Lambda(1405)$, for example, appears to be dynamically generated from meson-baryon interactions to some extent [15], which is also supported by recent LQCD calculations [16]. Models including vector meson-baryon interactions have predicted further dynamically generated states, for example states at 2 GeV with $J^P = 3/2^-$ and $3/2^-$ [17–19], which may have been observed in $K^0\Sigma^+$ photoproduction at the $K^*Y$ thresholds [20–22].

The BGO-OD experiment is ideally suited to study phenomena from hadronic reactions in a low momentum exchange region, where extended, molecular-like structure may manifest. The extremely forward charged particle acceptance, complemented by neutral particle reconstruction over a central region allows complicated final states to be reconstructed, enabling the study of phenomena from molecular or exotic structure in the strange quark sector.

2. THE BGO-OD EXPERIMENT AT ELSA

BGO-OD (Fig. 1) is a fixed target experiment using real, energy tagged photon beams at the ELSA electron accelerator facility [23]. An electron beam up to 3.2 GeV is incident upon a thin radiator to produce bremsstrahlung photons, with linearly and circularly polarised beams both available.

BGO-OD is composed of two distinct parts: a forward spectrometer ($\theta < 12^\circ$) for charged particle identification, and a central calorimeter region ($\theta = 25^\circ$–155$^\circ$) ideal for neutral meson reconstruction. A plastic scintillating detector (SciRi) covers the small acceptance gap between these.

The target is surrounded by an MWPC for charged particle track reconstruction. Surrounding this is a segmented cylinder of plastic scintillator material for charged particle identification via $\Delta E – E$. Outside of this is the BGO ball; a segmented calorimeter of 480 BGO crystals. The BGO ball is ideal for the reconstruction of photon four-momenta via electromagnetic showers in the crystals. The separate time readout per crystal, with a resolution of approximately 3 ns, enables clean identification of neutral meson decays (Fig. 2).

The forward spectrometer uses two scintillating fibre detectors (SciFi2 and MOMO) to track charged particles from the reaction vertex. Particles proceed through the open dipole magnet, operating at a maximum field strength of 0.45 T. Eight double layered drift chambers track particle trajectories after curvature in the magnetic field. The momentum is determined by the extent of deflection in the field, with a resolution of approximately 4%. Time Of Flight walls downstream from the drift chambers enable particle identification via the combination of momentum and $\beta$ (Fig. 3).

3. FORWARD $K^+Y$ PHOTOPRODUCTION

Figure 4a is the missing mass from selecting $K^+$ within a momentum dependent, 2$\sigma$ mass selection cut. With no additional selection criteria, peaks corresponding to $\Lambda(1116)$, $\Sigma(1193)$, $\Sigma(1385)$ and $\Lambda(1405)$ (almost mass degenerate), and $\Lambda(1520)$ are observed. The obtainable mass in this extremely low momentum exchange region extends to approximately 1900 MeV/c$^2$. The identification of neutral mesons in the BGO allows the separation of $K^+Y$ states where missing masses overlap. Figure 4b includes on the $y$-axis the mass missing from the $K^+\pi^0$ system. For $K^+\Lambda(1405) \rightarrow K^+\pi^0\Sigma^0$ and $K^+\Sigma(1385) \rightarrow K^+\pi^0\Lambda$, for
example, this missing mass should be the $\Sigma^0$ and $\Lambda$ masses respectively (as indicated on the figure). There is ongoing work to determine the $\Lambda(1405) \to \Sigma^0 \pi^0$ lineshape in this extremely low momentum exchange region.

Ground state hyperon photoproduction, $K^+\Lambda$ and $K^+\Sigma^0$ is virtually unconstrained by data at forward angles. The paucity of data and discrepancies between published data [24–27], prohibit accurate descriptions from isobar models and partial wave analyses (see for example, [28]). Data at forward angles is also crucially important for descriptions of hypernuclei electroproduction, where the required very low $Q^2$ is comparable to the photoproduction process (see for example, [29]). The excellent forward acceptance allows

Fig. 2. Neutral meson reconstruction in the BGO ball. (a) The “missing” mass recoiling from two photons versus the invariant mass of the two photon system. (b) Two photon invariant mass where the missing mass is consistent with the proton. Mean and sigma of peaks corresponding to $\pi^0$ and $\eta$ mesons are labelled inset.

Fig. 3. Charged particle identification with the forward spectrometer. (a) Particle $\beta$ versus momentum. Characteristic loci of protons, $K^+$, $\pi^+$ and $e^+$ are observed. (b) Particle mass reconstruction from $\beta$ and momentum: $m = p/\beta$. (c) The “missing” mass from selected forward protons. Peaks corresponding to single meson photoproduction channels labelled inset. (d) The same as (c), but zoomed into the $\eta'$ and $\phi$ mass region.
BGO-OD to resolve these discrepancies, with preliminary results shown below.

The missing mass for different centre of mass intervals are plotted in Fig. 5. The spectra are fitted using simulated $K^+\Lambda$ and $K^+\Sigma^0$ data, combined with background from $e^+$ and $\pi^+$ under the $K^+$ mass selection region. The background distribution was determined by an equivalent analysis selecting negatively charged particles, where the shape of the distribution from $\pi^-$ and $e^-$ background was identical.

At higher centre of mass energies, the broadening of the $K^+\Lambda$ and $K^+\Sigma^0$ peaks limits the accuracy to separate signal and background. This is mitigated by further selection criteria. Figure 6 shows the “Standard” analysis for events at $W = 1789$ MeV shaded in green.

With the identification of the $\pi^0$ from $\Lambda \rightarrow \pi^0 n$, most...
of the background can be suppressed (shaded red). For a clean identification of \( K^+ \Sigma^0 \), the decay photon from \( \Sigma^0 \rightarrow \gamma \Lambda \) can be identified in the BGO (shaded blue). Decay photon candidates are boosted into the missing momentum of the hyperon, where the energy of photon should equal the 77 MeV/c\(^2\) mass difference. This technique was used previously with the Crystal Ball calorimeter at the A2 collaboration [30].

Preliminary differential cross sections for \( \gamma p \rightarrow K^+ \Sigma^0 \) and \( \gamma p \rightarrow K^+ \Lambda \) at the extreme forward centre of mass polar angle, \( \theta_{CM}^{K^+} \), are shown in Fig. 7. These high statistics data are able to discriminate between previous conflicting data sets, and provide a crucial constraint to isobar and partial wave analyses in this extremely low momentum exchange region. The high angular resolution of the forward spectrometer (approximately 2°–3° in centre of mass polar angle) allows this region to be accurately described as \( \theta_{CM}^{K^+} \rightarrow 1 \) and work is ongoing binning into 0.02 \( \theta_{CM}^{K^+} \) intervals. Systematic errors are estimated to be approximately 7% of the cross section for most data points.

4. \( K^0 \) PHOTOPRODUCTION OFF HYDROGEN AND DEUTERIUM TARGETS

The unique setup of the BGO-OD experiment allows \( K^0 \) to be identified via both \( K^0 \rightarrow \pi^0 \pi^0 \) and \( K^0 \rightarrow \pi^+ \pi^- \) (neutral and charged decays respectively). Extensive data has been taken using both liquid hydrogen and deuterium (neutron) targets, to resolve a cusp-like structure at the \( K^\ast \) thresholds [20, 21] and measure over the predicted peak in the cross section [22]. Figure 8 shows \( K^0 \Sigma^+ \) reconstruction using a liquid hydrogen target. Figure 8a is the invariant mass of the \( \Sigma^+ \) after the identification of the \( K^0 \) via the charged decay. The real signal in blue is clear above a background described by simulated data in green, which is dominantly uncorrelated \( p \pi^+ \pi^- \). There is ongoing work to implement the MWPC track information, where the detached decay vertex of the \( K^0 \) (\( c\tau \approx 2.7 \) cm) can be identified to suppress background. Figure 8b is the \( K^0 \) invariant mass identified from the neutral decay. A Gaussian and polynomial function are fitted to the signal and background respectively.
Figure 9a shows the $K^0$ invariant mass peak above background, identified via the neutral decay using the deuterium target data set. The simulated data in red gives a good agreement to the signal shape. To separate $K^0\Sigma^0$ from the $K^0\Sigma^+$ and $K^0\Lambda$ channels, the decay photon from $\Sigma^0 \rightarrow \gamma\Lambda$ can be identified in the BGO, in the same way as described in Section 3. A peak can be observed at the $\Sigma^0 - \Lambda$ mass difference of 77 MeV, shown in Fig. 9b. Simulated data is shown in red.

5. FUTURE OPPORTUNITIES

Hypernuclei provide a natural laboratory to probe hyperon-nucleon (YN) interactions, hyperon-hyperon (YY) interactions, or three body interactions. These are poorly experimentally constrained compared to NN interactions, but are vital in order to construct a unified SU(3)$_{\text{flavour}}$ description of baryon interactions. Furthermore, many astrophysical phenomena strongly depend upon YN interactions. The Hyperon Puzzle, for example, is the difficulty to reconcile measured neutron star masses with equation of
state calculations when including expected contributions of strange hadronic matter (see, for example [32]). BGO-OD may be able to uniquely complement existing hypernuclei facilities, using a real energy tagged photon beam. For $K^+\Lambda$ photoproduction from a nuclear target, if the $K^+$ enters the forward spectrometer, a sizeable proportion of $\Lambda$ will remain bound within the Fermi surface of the recoiling nucleon. Energy resolution will not permit the search for new hypernuclei states, however measurements of angular distributions, differential cross sections, and lifetime measurements of known states may be accessible. Targets which may be spoiled by intense electron beams could also be used with the BGO-OD real photon beam [33].

As a demonstration that BGO-OD can access kinematics similar to hypernuclei photoproduction, Fig. 10 shows an example of coherent pion photoproduction, using a short commissioning data set with a carbon target. Low beam energies, and a selection of forward limited the momentum transferred to the residual nucleus and increased the probability of coherent production. This can be seen in Fig. 10a, where the peak in the data corresponds to the difference in the measured $\pi^0$ energy to the energy calculated from the beam energy and $\pi^0$ angle, assuming a coherent event. In a similar method employed in [34], the decay photon from the nuclear de-excitation $^{12}\text{C}^* \to ^{12}\text{C} + \gamma(4.4 \text{ MeV})$ was also identified. Figure 10b shows a peak consistent with the 4.4 MeV gamma ray.
Figure 10c is the angle between this photon and recoiling nucleus. This is a pure E2 transition $(J^p : 2^+ \to 0^+)$, where the distribution should follow a $\sin^2(2\alpha)$ shape. Despite no efficiency corrections, there appears good agreement between the fit and the data.

It may also be possible to study the YN interactions via final state interactions (FSI) using a deuterium target and identifying $\gamma p(n) \to K^+ \Lambda(n)$. FSI are dominated by YN interactions in the case of forward $K^+$, and there are model predictions of the effects of these interactions in differential cross sections and polarisation observables [35].

ACKNOWLEDGMENTS

We thank the staff and shift-students of the ELSA accelerator for providing an excellent beam.

FUNDING

This work was supported by the Deutsche Forschungsgemeinschaft Project no. 50165297.

REFERENCES

1. E. Klempt and J. M. Richard, Rev. Mod. Phys. 82, 1095 (2010).
2. R. Aaij, et al., Phys. Rev. Lett. 115, 072001 (2015).
3. M. Gell-Mann, Phys. Lett. 8, 214 (1964).
4. R. L. Jaffe, Phys. Rev D 15, 267 (1977).
5. D. Strottman, Phys. Rev D 20, 748 (1979).
6. A. Manohar and H. Georgi, Nucl. Phys. B 234, 189 (1984).
7. L. Ya. Glozman and D. O. Riska, Phys. Rep. 268, 263 (1996).
8. Jia-Jun Wu, R. Molina, E. Oset, and B. S. Zou, Phys. Rev. Lett. 105, 232001 (2010).
9. N. A. Törnqvist, Phys. Lett. B 590, 209 (2004).
10. R. H. Dalitz, T. C. Wong, and G. Rajasekaran, Phys. Rev. 153, 1617 (1967).
11. P. B. Siegel and W. Weise, Phys. Rev. C 38, 2221 (1988).
12. N. Kaiser, T. Waas, and W. Weise, Nucl. Phys. A 612, 297 (1997).
13. C. Garcia-Recio, M. F. M. Lutz, and J. Nieves, Phys. Lett. B 582, 49 (2004).
14. M. F. M. Lutz and E. E. Kolomeitsev, Phys. Lett. B 585, 243 (2004).
15. D. Jido, J. A. Ollier, E. Oset, A. Ramos, and U.-G. Meissner, Nucl. Phys. A 725, 181 (2003).
16. J. M. M Hall, et al., Phys. Rev. Lett. 114, 132002 (2015).
17. P. Gonzalez, E. Oset, and J. Vijande, Phys. Rev. C 79, 025209 (2009).
18. S. Sarkar, et al., Eur. Phys. J. A 44, 431 (2010).
19. E. Oset and A. Ramos, Eur. Phys. J. A 44, 445 (2010).
20. R. Ewald, et al., Phys. Lett. B 713, 180 (2012).
21. R. Ewald, et al., Phys. Lett. B 738, 268 (2014).
22. E. Oset and A. Ramos, Eur. Phys. J. A 44, 445 (2010).
23. W. Hillert, Eur. Phys. J. A 28, s01, 139 (2006).
24. R. Bradford, et al. (CLAS Collab.), Phys. Rev. C 73, 035202 (2006).
25. K.H. Glander, et al. (SAPHIR Collab.), Eur. Phys. J. A 19, 251 (2004).
26. B. Dey, et al., Phys. Rev. C 82, 025202 (2010).
27. M. E. McCracken, et al., Phys. Rev. C 81, 025201 (2010).
28. D. Skoupil and P. Bydzovsky, Phys. Rev. C 97, 025202 (2018).
29. T. Mizutani, C. Fayard, G. H. Lamot, and B. Saghai, Phys. Rev. C 58, 75 (1998).
30. T. C. Jude, et al., Phys. Lett. B 735, 112 (2014).
31. A. V. Anisovich, et al., Eur. Phys. J. A 34, 243 (2007).
32. A. Gal, E. V. Hungerford, and D. J. Millener, Rev. Mod. Phys. 88, 035004-39 (2016).
33. P. Achenbach and J. Pochodzalla, Private communication (2018).
34. C. M. Tarbert, D. P. Watts, et al., Phys Rev. Lett. 100, 13 (2008).
35. K. Miyagawa, T. Mart, C. Bennhold, and W. Gloeckle, Phys. Rev. C 74, 034002 (2006).