Measurement of the $\gamma n \rightarrow K^0\Sigma^0$ differential cross section over the $K^*$ threshold

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The differential cross section for the quasi-free photoproduction reaction $\gamma n \rightarrow K^0\Sigma^0$ was measured at BGOOD at ELSA from threshold to a centre-of-mass energy of 2400 MeV. Close to threshold the results are consistent with existing data and are in agreement with partial wave analysis solutions over the full measured energy range, with a large coupling to the $\Sigma(1900)$ evident. This is the first dataset covering the $K^*$ threshold region, where there are model predictions of dynamically generated vector meson-baryon resonance contributions.

I. INTRODUCTION

Associated strangeness photoproduction is a crucial tool to study nucleon resonance spectra. A main motivation of the measurement of $KY$ channels over the last 15 years has been to search for missing resonances which may only couple weakly to $NN$ final states [1,2]. $K^0\Sigma^0$ has a threshold at 1690 MeV, rendering the channel ideal to probe the third resonance region where many $s$-channel resonances up to high-spin states lie. Studying this reaction is therefore a requirement to constrain phenomenological models and partial wave analyses (PWA) which attempt to describe the nucleon excitation spectrum of known resonances. This includes PWA with dynamical coupled-channel frameworks [3,4], isobar models [7,11], and models incorporating Regge trajectories [15,17] to fix $t$-channel contributions. $K^0$ photoproduction data is also complementary to $K^\pm$ photoproduction as hadronic couplings can be related via isospin symmetry [18] and the absence of $t$-channel pseudo-scalar $K$ exchange ensures $s$-channel resonance contributions are more dominant (however there are still $K^*$ $t$-channel contributions).

Additionally, calculations based on vector meson-baryon interactions via coupled-channel unitary frameworks have predicted dynamically generated states contributing to $K^0\Sigma$ channels. A model by Ramos and Oset [19] explained a cusp-like structure observed in $K^0\Sigma^+$ photoproduction at the $K^*$ threshold from the destructive interference between amplitudes containing $K^+\Lambda$ and $K^+\Sigma$ intermediate states, and magnified by a proposed $N^*(2030)$ vector meson-baryon dynamically generated resonance at the $K^*\Sigma$ threshold. The model predicts that for photoproduction off the neutron, the interference of these amplitudes is constructive, resulting in a peak structure in the channel $\gamma n \rightarrow K^0\Sigma^0$.

The complexity of identifying the $K^0\Sigma^0$ final state has led to a lack of data compared to the $K^+\Lambda$ and $K^+\Sigma$ channels, where the only available dataset is from the A2 Collaboration and covers the first 150 MeV from threshold.

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old [21]. Motivation for the study of $K^0\Sigma^0$ photoproduction is therefore twofold. Firstly, to constrain phenomenological models and PWA used to describe the nucleon excitation spectrum. Secondly, to provide the first dataset over the $K^*$ threshold region in an attempt to discriminate between models including “conventional” $s$-channel resonances and models predicting meson-baryon dynamically generated resonances beyond a $qqq$ valence quark configuration. This paper reports a measurement of the differential cross section of the reaction $\gamma n \rightarrow K^0\Sigma^0$ from threshold to 2400 MeV, achieved with the BGOOD experiment [22] at the ELSA [23, 24] facility at Bonn University.

II. EXPERIMENTAL SETUP AND RUNNING CONDITIONS

The presented data was taken using an ELSA electron beam of 2.9 GeV incident upon a thin radiator to produce a collimated beam of bremsstrahlung photons. The photon energies were determined by measuring the post bremsstrahlung electron momenta in the Photon Tagger. Two data taking periods with an 11 cm long target containing either liquid deuterium or hydrogen with identical beam conditions were used. The hardware trigger, which was the same for both data taking periods, required a signal in the Photon Tagger and an energy deposition of at least 200 MeV in the BGO Rugby Ball. Details on the characterization and modelling of the trigger are in Ref. [25].

The integrated photon flux from threshold to a centre-of-mass energy of 2400 MeV was 6.39 · 10^{12} and 5.78 · 10^{12}, respectively.

The BGOOD experiment is composed of a magnetic forward spectrometer complemented with a central BGO calorimeter [22, 23]. The BGO Rugby Ball, is composed of 480 BGO crystals, which surround the target and cover a polar angle range of $25^\circ < \theta_{lab} < 155^\circ$. Each crystal spans 6° to 10° in the polar angle $\theta_{lab}$, 11.25° in the azimuthal angle $\phi$ and has a depth of 24 cm, corresponding to 21 radiation lengths. The time resolution of 2 ns allows for a clean separation of multiple photons for neutral meson reconstruction. A minimal required energy deposition of 1.5 MeV per individual crystal and 25 MeV per crystal cluster suppresses neutron background. A barrel type arrangement of plastic scintillators interior to the BGO Rugby Ball is utilized to veto charged particles. The forward spectrometer covers the angular range $1^\circ < \theta_{lab} < 12^\circ$. A series of tracking detectors sandwiching the open dipole magnet [22] are used for charged particle identification and momentum reconstruction. The small intermediate range is covered by a segmented array of 96 plastic scintillators for charged particle detection.

III. SELECTION OF $\gamma n \rightarrow K^0\Sigma^0$ EVENTS

$K^0$ candidates were identified via the decay $K^0_S \rightarrow \pi^0\pi^0 \rightarrow (\gamma\gamma)(\gamma\gamma)$ in the BGO Rugby Ball. Two photon pairs were required where the invariant masses were within 30 MeV/$c^2$ of the $\pi^0$ mass, which corresponds to $\pm 2\sigma$.

Three additional selection criteria were used to isolate the reaction channel. First, the missing mass to the $K^0$ candidates was required to be consistent with the $\Sigma^0$ mass, lying between 1150 and 1250 MeV/$c^2$. Secondly, identification of the photon from the decay $\Sigma^0 \rightarrow \gamma\Lambda$ was required. To achieve this, photons which were not identified as a $\pi^0$ decay photon were boosted into the rest frame of the $\Sigma^0$. Fig. 1 shows the energy of the boosted $\gamma$ in this frame, where a peak at 75 MeV from the two-body $\Sigma^0$ decay is expected. A small peak is visible over a large background at this energy, which is consistent with the simulated data. The decay photon from the channel $\gamma p \rightarrow K^+\Sigma^0$ is also shown, where the signal is cleaner.

Events were selected where the photon energy was between 54 MeV and 96 MeV, corresponding to $\pm 3\sigma$.

The final selection criterion required the detection of exactly two charged particles consistent with the decay $\Lambda \rightarrow \pi^-\mu^+\nu$. The $\Lambda$ momentum was calculated from the missing momentum to the $K^0$ and the photon from the

1 To correctly determine the centre-of-mass energy the Fermi momentum of the target particle needs to be known, however since this was not possible event by event, the target was assumed to be at rest.

2 This technique was used to identify the $K^+\Sigma^0$ channel in Ref. [26].
counts / 4 MeV/c
ground, for example misidentifying a low mass shoulder originating from combinatorial background, where increasing the selection criteria removes the π as a two π selection cuts affect the invariant mass distribution of the momentum constraint. Fig. 3 shows how the different known target Fermi-momentum prevented a full four of the detected charged particles combined with the unmeasured Fermi-momentum of the target nucleon within the deuteron.

For a given event, all combinations of particle assignment to the five neutral and two charged particles were retained if they passed the selection criteria. No kinematic fit was applied as the lack of energy information of the detected charged particles combined with the unknown target Fermi-momentum prevented a full four-momentum constraint. Fig. 3 shows how the different selection cuts affect the invariant mass distribution of the two π0 system. Fig. 3(a) depicts simulated γn → K0Σ0 data, where increasing the selection criteria removes the low mass shoulder originating from combinatorial background, for example misidentifying a γ from the Σ0 decay as a π0 decay γ. This background is small after including all selection criteria and was estimated as contributing a systematic uncertainty of 3%. Fig. 3(b) depicts real data using a deuterium target, where the peak corresponding to the K0 invariant mass becomes increasingly pronounced from the background distribution with increased selection criteria.

Background from reaction channels off the proton in the deuteron was subtracted by applying the same selection criteria to the liquid hydrogen target dataset. The hydrogen data was scaled according to the ratio of the photon beam flux and target densities. To account for the broadening of momentum and mass distributions caused by the unmeasured Fermi motion, the proton target four-momentum in the computation of kinematic quantities was smeared according to the momentum distribution of nucleons in deuterium [27]. Fig. 3 shows the scaled hydrogen data together with the deuteron data and the resulting spectrum after subtracting hydrogen data from deuterium data.

Two methods were used to fit to the K0Σ0 signal and remaining background. The first used simulated phase-space distributions of the dominant background channels, referred to later as PS. Simulated data was used to determine the fraction of background channel events passing the selection criteria. The dominant channels were found to be multi-pion production (γn → 3πN and γn → 4πN) and γn → ηN, all of which gave almost identical 2π0 invariant mass spectra. The required topology of five neutral and two charged particles was satisfied by these background channels either exactly, or by missing a particle in small acceptance gaps in the experimental setup, or by falsely identifying an additional particle due to split-off clusters in the BGO Rugby Ball and particles scattering off detector components. The channel γn → 3π0n
was chosen as representative of the multi-pion channels and used to describe the background distribution. Other channels were found to provide negligible contributions.

The second method, later referred to as RD, used real data to describe the background. To generate this distribution, a $K^0$ candidate and an additional photon were required, however this photon was not identified as a $\Sigma^0$ decay photon candidate and there was no selection criteria on charged particle multiplicity or topology.

In both cases, the signal shape was phase-space generated using simulated $K^0\Sigma^0$ data and a full Geant4 [28] simulation of the experimental setup. RooFit [29] was used to fit the data with a maximum likelihood fit. Fig. 5 shows fit examples using the PS background description in the angular range $0.2 < \cos \theta^\text{CM}_K < 0.5$, where $\cos \theta^\text{CM}_K$ is the cosine of the centre-of-mass polar angle of the $K^0$.

The limited statistical precision reduces the usefulness of $\chi^2$ distributions. Instead a hypothesis test was performed to prove the necessity of the simulated signal distribution to describe the data. The test gives the probability of the data following a given distribution which is only comprised of background, the hypothesis of which is denoted $H_0$. This is achieved by creating 10000 Monte Carlo (MC) samples from the background distributions each with the same statistical precision as the real data distributions. Each MC sample is fitted twice. The first fit is with background (BG) only, the second is with background and signal (BG+S), $\zeta^2$, given in Eq. 1 is calculated for each fit, where $N_{\text{fit}}$ and $N_{\text{data}}$ are the number of events in each bin of the fitted spectrum for the fitted function and the data respectively, and $\Delta N_{\text{data}}$ is the corresponding error.

$$\zeta^2 = \sum_{\text{bins}} \left( \frac{N_{\text{fit}} - N_{\text{data}}}{\Delta N_{\text{data}}} \right)^2 \quad (1)$$

For each MC sample the difference is calculated:

$$\Delta \zeta^2 = \zeta^2(BG) - \zeta^2(BG + S) \quad (2)$$

This is repeated for the real data, denoted $\Delta \zeta^2_{\text{real}}$. The distribution of $\Delta \zeta^2$ for the 10000 MC samples under the hypothesis $H_0$ is denoted $g(\Delta \zeta^2 | H_0)$.

A measure of agreement with $H_0$ can then be calcu-
tional particles in the central calorimeter further reduces

\[ K \]

This includes the branching ratios of the \( K \)
which limits the efficiency to \( \approx \theta \)
a function of energy for four different cos

center-of-mass energies 1796 MeV and 2040 MeV respec-
dered yield in the angular bin 0
\[ 0 \]
near threshold, with for example 16 % and 2 % of the ex-
ments from Ref. [31] were subsequently used to determine
\[ p \]
the fitting methods described above.

Fig. 6 shows \( p \) using the two background descriptions
\[ 0 \]
PS and RD. Both descriptions generally agree with each other. \( p \) is low where the signal gives a significant con-
tribution to the fitted spectrum, indicating that a back-
ground distributions alone is not sufficient to describe the data.

An alternative method to separate signal and back-
ground was made using side band subtraction tech-
tiques [30]. The resulting yields were in agreement to

\[ p = \int_{\Delta \zeta_{\text{real}}}^{\infty} g(\Delta \zeta^2 | H_0) \] (3)

Fitting to the \( K^0 \) invariant mass does not discriminate
between \( \gamma n \rightarrow K^0 \Sigma^0 \) and \( \gamma n \rightarrow K^0 \Lambda \), however, the sele-
ction criteria strongly suppressed the contribution from
\[ 0 \]
\( \gamma n \rightarrow K^0 \Lambda \). Simulated data and cross section measure-
ments from Ref. [31] were subsequently used to determine
and subtract the remaining contribution of \( K^0 \Lambda \) to the
\[ 0 \]
\( K^0 \Sigma^0 \) yield. This was a small contribution and largest
near threshold, with for example 16 % and 2 % of the ex-
ttracted yield in the angular bin 0.2 \( < \cos \theta_{\text{CM}}^0 < 0.5 \) at center-of-mass energies 1796 MeV and 2040 MeV re-
spectively.

The reconstruction efficiency is depicted in Fig. 7 as
a function of energy for four different \( \cos \theta_{\text{CM}}^0 \) ranges.
This includes the branching ratios of the \( K^0 \) eigenstates
\[ 0 \]
\( K^0 \) and \( K^0 \) and the detected \( K^0 \) and \( \Lambda \) decay modes,
which limits the efficiency to \( \approx 10 \) %. Requesting 5 neu-
tral particles in the central calorimeter further reduces

\[ \text{Source} \] | \% error |
--- | --- |
Photon flux | 4 |
Target length | 1 |
Beam energy calibration | 1 |
Modelling of hardware triggers | 1 |
\( \pi^0 \) identification | 3 |
\( \Sigma^0 \rightarrow \gamma \Lambda \) identification | 6 |
Selection of the missing (\( \Sigma^0 \)) mass | 3 |
Charged particle identification | 4 |
Combinatorial background | 3 |
Subtraction of hydrogen background | 5 |
\( K^0 \Lambda \) subtraction | 1 |
Summed in quadrature | 11 |

**TABLE I.** Sources and values of systematic uncertainties (not including the fitting systematic uncertainty).

the efficiency to below 1 %. No structures are seen that
could cause artefacts in the measured cross section.

Table I shows the systematic uncertainties. The iden-
tification of the photon from the decay \( \Sigma^0 \rightarrow \gamma \Lambda \) and the sub-
traction of hydrogen background are the dominating
uncertainties at 6 % and 5 % of the measured cross sec-
tion, respectively. The uncertainty on the photon flux
normalization was determined as explained in Ref. [25].
Systematic uncertainties specific to this analysis were esti-
ated by varying the selection criteria at each step and
determining the effect on the extracted cross section. The
systematic uncertainty of fitting is determined as the dif-
ference between the cross section of the two methods to
fit the background (RD and PS). While all other system-
atic uncertainties are a constant fraction of the measured
cross section and therefore can only change the global
scaling of the dataset, the fitting uncertainties permit
point to point fluctuations of the data points. These un-
certainties are therefore shown separately in Fig. 8.
IV. RESULTS

The differential cross section for $\gamma n \rightarrow K^0\Sigma^0$ is shown in Fig. 8 as a function of energy in four bins in $\cos \theta^K_{CM}$. The two methods used to describe and subtract background show a good agreement, with the exception of the most backward angle bin, $-0.7 < \cos \theta^K_{CM} < -0.4$, where there is a discrepancy of up to 0.1 $\mu$b/sr in the first two energy bins from threshold to $W = 1823$ MeV. This is due to limited phase space in the $2\pi^0$ invariant mass spectrum preventing a clean separation of signal and background. The data of Akondi et al. (A2 Collaboration) [21] are shown as the blue squares from threshold to $W = 1855$ MeV. When combining the statistical and systematic uncertainties of both datasets (the systematic uncertainty of the A2 data varies from 0.001 to 0.004 $\mu$b/sr), there is reasonable consistency over most of the kinematic coverage, however the A2 data generally appears higher. This is most pronounced at the two most backward angles at $W = 1855$ MeV, where there is a discrepancy of approximately $1\sigma - 2\sigma$ beyond the combined uncertainties.

Calculations from the Kaon MAID effective Lagrangian model [11] and the Bonn-Gatchina Partial Wave analysis (BnGa) [32] are shown as the magenta and orange lines respectively. The BnGa calculation includes dominant contributions from $S_{11}$ and $P_{11}$ partial waves and gives an agreement to the data over the full measured $\cos \theta^K_{CM}$ range. The Kaon MAID calculation also appears to have a reasonable agreement in the two most forward $\cos \theta^K_{CM}$ intervals, whereas in the two backward intervals the calculation lies approximately between this data and the A2 data. The Kaon MAID model includes resonant contributions from $\Delta(1650)1/2^-, N(1710)1/2^+$, $N(1720)3/2^+$, $\Delta(1900)1/2^-$ and $\Delta(1910)1/2^+$. The peak at $W = 1900$ MeV observed in the data most promi-
nently in the interval $-0.10 < \cos \theta_{CM}^K < 0.20$ is described by the large coupling to the $\Delta(1900)1/2^-$. The model by Ramos and Oset [19] predicted a peak at the $K^*$ threshold caused by a vector-meson baryon dynamically generated state. This dataset does not exclude a structure at $W \approx 2040$ MeV and $0.20 < \cos \theta_{CM}^K < 0.50$, however the current statistical precision does not permit a conclusion and further data is required to discriminate between phenomenological models in this energy range.

Contributions from final state interactions can not be disregarded without additional studies, however calculations for quasi-free photoproduction off the deuteron of $K^+Y$ [33, 34] show them to be negligible over the kinematic range presented here.

V. CONCLUSIONS

A first measurement of the reaction $\gamma n \rightarrow K^0\Sigma^0$ is presented from threshold to 2400 MeV, spanning the region of the $K^*$ threshold. The channel was identified via the decays $K^0_S \rightarrow \pi^0\pi^0$ and $\Sigma^0 \rightarrow \Lambda\gamma \rightarrow (p\pi^-)\gamma$ at the BGOOD experiment. Two different methods were used to describe background from other reaction channels passing the selection criteria, which after fitting to $2\pi^0$ invariant mass spectra to extract the signal proved compatible. The data are consistent with existing data used to describe background from other reaction channels, however the current statistical precision does not permit a conclusion.

Vlasov model numbers 824093.

In BnGa no resonances are put in a priori. Instead poles emerge from the K Matrix formalism within specific partial waves. What is included here is S11 and P11 partial waves.

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