Recent Results of the BGO-OD Experiment at ELSA Facility

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Abstract. The results obtained at the BGO-OD experiment with the BGO calorimeter, equipped with the new electronic readout based on sampling ADCs, during the tests performed with the beam time of March and June 2012 are presented. The proper functioning of the apparatus has allowed the reconstruction of the pseudo-scalar mesons $\pi^0$ and $\eta$ invariant masses. The simulation of the $\eta'$ photoproduction reaction prepared for a proposal to the joint ELSA-MAMI Physics Advisory Committee is also presented.

1. Introduction

The excitation spectrum of the nucleon is the most important ground where to test our understanding of QCD in the strong-coupling regime and the study of baryon resonances plays the same role for understanding the nucleon structure as the nuclear spectroscopy played for the investigation of the nucleus structure.

There are major experimental, theoretical and computational efforts that aim to explore both the spectrum and the structure of excited nucleons. The dominant decay channel of nucleon resonances is the hadronic decay via meson emission [1]. Photoproduction of mesons, which carries information on strong and electromagnetic decay properties, therefore provides a very valuable tool for their study.

Dedicated experimental programs exist to perform accurate measurements of meson photo- and electro-production off the nucleon in order to discover its excitations, and determine its internal structure. A new generation of electron accelerators equipped with tagged photon facilities have opened the way to meson photoproduction experiments of high sensitivity and precision [2]. The BGO-OD experiment at the ELSA facility at Bonn (see Figure 1) involves the use of a Bremsstrahlung tagged and polarized photon beam of energy between 0.7 and 3.2 GeV, a large solid angle high resolution BGO calorimeter and the Open Dipole spectrometer equipped with tracking detectors. This apparatus will be used to measure polarisation observables and cross sections in the photoproduction of pseudo-scalar and vector mesons off an hydrogen or deuterium target.

2. Experimental Setup

A schematic view of the experimental apparatus located at the S-beamline of Bonn is shown in Figure 2. The Electron Stretcher Accelerator (see Figure 1) consists of three stages (injector LINAC, booster synchrotron and stretcher ring) and provides a beam of polarized and unpolarized electrons with a tunable energy up to 3.5 GeV. The extracted bunched electron beam impinges on a radiator in the S-beamline. Scattered electrons produce coherent and incoherent bremsstrahlung photons of energy $0.1 \div 3\,\text{GeV}$.
The BGO-OD detector setup is a combination of a central detector system and a forward spectrometer for charged particles, completed by a photon tagging system. The resolution of the tagger is about $1\% \div 2\%$ of the incident electron beam.

In the polar angular region between 25° and 155° we encounter:

- The BGO ($Bi_4Ge_3O_{12}$) Rugby Ball, a large acceptance calorimeter (see Figure 3) able to measure multi-photon event yield with excellent energy resolution (3% FWHM at 1 GeV). The design of the calorimeter has been performed in order to have a constant thickness in every direction and a central hole of radius 100 mm for the passage of the beam, target and inner detector housing. The resulting structure is made of 480
truncated pyramidal crystals of 240 mm length (corresponding to 21 radiation lengths) arranged in a $15 \times 32$ matrix covering the polar angles from $25^\circ$ to $155^\circ$ and the whole azimuthal angles, corresponding to a total solid angle $\Delta\Omega$ of 11.3 sr. The mechanical structure consists of 24 carbon fiber baskets, each containing 20 crystals, and supported by an external steel frame. The baskets are divided into cells to keep the crystals mechanically and optically separated.

- A cylinder of 32 plastic scintillator bars, for the measurement of the $\Delta E$ of charged particles, which allows, in combination with the energy released in the calorimeter, the discrimination between charged and neutral particles and the identification of charged particles (protons and pions).

- Two cylindrical multi wire proportional chambers (MWPC), under construction, for the reconstruction of trajectories from charged particles. Each chamber is made of two coaxial cylindrical cathodes which are segmented into strips, helically wound in opposite directions. The anode array consists of equally spaced wires stretched parallel to the cylinder axis in the middle of the active area (gas gap $\sim 8\ mm$). The geometrical parameters are tuned to fit inside the carbon structure of the BGO and around the target nose.

- The target cell and the cryogenic system, which are located directly behind the beam dump along the beam direction. The cell is contained in a vacuum pipe, which guarantees the thermal insulation and is surrounded hermetically by the central detectors. The target cell is a 4 cm diameter Aluminum cylinder, closed by thin mylar windows at the two sides for the passage of the beam. Two different lengths of the cell are available (6 and 11 cm) in order to fulfill different experimental requirements. The target cell can be filled either with liquid Hydrogen ($H_2$) or Deuterium ($D_2$).

To cover the forward angular region between $\theta_{lab} = 25^\circ$ and $\theta_{lab} = 8^\circ$ an azimuthally-symmetric Multi-gap Resistive Plate Chamber detector (MRPC) will be installed between the BGO and the MOMO detector. The detector is divided into 16 phi sectors.

Figure 3. BGO Calorimeter.
and it has in total 480 channels. Each sector in the azimuthal angle consists of two
stacks. The expected spatial resolution $\sigma_s$ is $1 \text{ cm}^2$ and the time resolution $\sigma_t$ is about
50 ps.

The polar angular region of forward angles ($\theta < 12^\circ$) is covered by the B1-
magnetic field spectrometer that uses a dipolar field of about 0.5 T for the separation,
identification and measurement of the momentum (3% resolution) of charged particles
emitted in the photoproduction processes.

For this purpose, the spectrometer is equipped with:
- MOMO and SciFi2 that are scintillating fiber detectors for the reconstruction of
the tracks in front of the magnet [6].
- Eight double layer drift chambers (DCs) which are built at PNPI of Gatchina, for
the tracking of charged particles behind the spectrometer. These are arranged in four
different orientations, the vertical wires to measure the x-coordinate, the horizontal ones
to measure the y-coordinate, and tilted by $\pm 9^\circ$ from vertical for u- and v-coordinate
measurement.
- A time-of-flight (TOF) detector, which is an essential component for particle
identification, because it provides time of flight measurements for charged particles. It
covers the region $\theta < 8^\circ$ and $\theta < 12^\circ$ in the vertical and in the horizontal directions,
respectively, at a distance of 5 m downstream of the target [6].

3. BGO calibration procedure

The absolute calibration of the Bgo Rugby Ball was obtained using the 1.275 MeV
photons ($E_{\text{source}}$) emitted by three $^{22}\text{Na}$ sources located inside the BGO cylindrical
hole. The response of the 480 crystals was equalized using a procedure that sets all
the photomultiplier (PM) gains, varying their high voltages. Thirty Wiener Sampling
ADC modules have been used for the acquisition of the signals of the BGO detectors.
The modules allow the extraction of the total deposited energy and the starting time of
the signal. The equalization is strictly necessary, because a threshold on the hardware
sum of the energy released in the BGO is used as a trigger for the experiment. After
the equalization, for the same energy released, the response of the PM associated to
each crystal will be located at the same ADC channel. For the calibration procedure
an internal trigger which is provided by the ADC, when a signal overcomes a certain
threshold, was used; it was chosen in order to guarantee the same statistics on all the
crystals, which a global trigger on the hardware sum of the energies of all the crystals
could not insure. In Figure 4 a schematic representation of the experimental chain of
calibration is shown: the output signal from the phototube, coupled to the crystal, is
sent to a mixer that delays, eventually attenuates and sums over the signals, and then
it is sent to the ADC module for the readout.

To obtain the calibration constants for each channel, we fix the PM voltages so that
the response to the energy of the second peak of the source is located at the channel 60
of the ADCs. The channel is fixed within a tolerance of $\pm 3\%$, which, in any case, does
not affect the calibration of the data, since the calibration constant of each crystal is registered and used for the offline energy conversion.

The calibration procedure enables us to monitor the position of the peaks during the time (without changing the HV, just recording their position). It requires that the attenuators of the mixers and the beam are switched off.

The calibration constant of each crystal may change during time due to two principal reasons: variation in the crystal light output due to temperature effects and variation in the PM gain. Gain variations of the photomultipliers may occur as a consequence of the following effects:

- photocathode temperature variation;
- instability in the high voltage power supply;
- aging of the cathode and dynode materials;
- voltage dividers instability [7].

In Figure 5 the azimuthal distribution ($\phi = 1 \div 32$) of the values of the calibration constants for two BGO crowns ($\theta = 1, 2$) related to different set of calibrations is shown. The blue squares refer to the equalization on February 15th, 2012; it is possible to see that all the responses are set within a maximum dispersion of ±3% (except for crystal $\theta = 2, \phi = 14$, whose PM had low gain). For the calibration constants on March 1st and March 5th, the fluctuations of the position of the second peak is about 1-2 channels which means an uncertainty of about 1.6%-3.2% of the energy. More fluctuations occur in the case of the comparison between the calibration constants obtained on February 15th and

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**Figure 4.** Scheme of the experimental calibration chain.

**Figure 5.** Calibration constants; the blue squares refer to the equalization on February 15, 2012; the red triangles to the calibration on March 1, 2012; the black stars to the calibration on March 5, 2012.
March 1st. The position of the second peak changes of about six channels corresponding to an uncertainty of 9.8%. When a new calibration procedure is performed at a certain time and new calibration constants are recorded, these can be used for the correct conversion channels-energy at that time. But if strong differences with respect to the previous calibration occur, we can only infer that an uncertainty in the energy conversion arose in the period in-between. For this reason it is necessary to repeat the calibration procedure often in order to reduce the uncertainty in the behaviour of the calibration constants between two consecutive calibrations.

4. Preliminary results of the beam time tests.

The beam time tests were performed with the following experimental conditions: electron beam energy 2.5 GeV, two different BGO trigger conditions (the threshold of the energy sum of all the 15 crowns higher than 400 MeV and with a BGO-trigger where the threshold of the energy sum of the first 13 crowns was higher than 200 MeV), the target filled of liquid Hydrogen $H_2$, and the totally equipped BGO electronic readout. In Figure 6 a three-dimensional mapping of the BGO ball with the number of hits, when there was no beam and the accelerator was switched off, is represented. x and y coordinates are the number of the crown ($\theta$) and the azimuthal distribution ($\phi$) of crystals of the same crown, respectively. In the left part, the number of hits with energy threshold $>1.0\, MeV$ is shown. Here, the three sources of $^{22}Na$ appear clearly. In the right part, the number of hits with energy threshold $>20\, MeV$ is also shown.

![Figure 6](image)

Figure 6. In the left part, the number of hits with energy threshold $>1.0\, MeV$ is shown. Here, the three sources of $^{22}Na$ appear clearly. In the right part, the number of hits with energy threshold $>20\, MeV$ is also shown.

In Figures 7 and 8 (indexes from 1 ÷ 240 and from 241 ÷ 480 correspond to the two
halves of the BGO, left and right respectively, with respect to the incident beam) we show the energy and time distributions per index of crystals, respectively.

Figure 7. Energy distribution per index of the 480 crystals of the BGO.

As one can see, there is a strong global difference between the time measured in the two halves, which is trivially due to differences in the cable lengths, but also a little difference can be observed between the forward or backward crowns (indexes 1-48 and 192-240 for the left part; indexes 241-248 and 432-480 for the right part) probably which is probably due to the different electron transit time in the phototubes of different sizes. The analysis was performed with the Explora code [4] using the calibrated energy and time information of the deposited energy in the BGO crystals. To reconstruct the energy and position of incident particles in the BGO, the first step was the identification of photons from 'clusters' of adjacent crystals due to electromagnetic showers from bremsstrahlung and pair production.

Figure 8. Starting time distribution versus the index of the 480 used crystals.
To identify the detected particles, without the charged particle identification (the scintillator barrel was still not in operation during the beam time), the size of reconstructed clusters within the BGO was used. A cluster of three or more crystals was assumed to be a candidate photon, a cluster with only one crystal is a possible candidate proton or a charged pion [5].

Particularly, we observed that when the total energy deposit is below about 300 $MeV$ there is much low energy background to discern any structure in the spectrum. However above approximately 400 $MeV$ there is a concentration of events with the invariant mass close to the expected $\pi^0$ mass, and a smaller shoulder above 500 $MeV$ is consistent with the mass of the $\eta$ meson.

![Figure 9. Two photon invariant mass spectrum taken with the BGO calorimeter in March 2012. [5,6]](image)

In Figure 9, the invariant mass of the two candidate photons is plotted for a total deposited energy > 400 $MeV$.

5. Monte Carlo estimation of the $\Sigma$ beam asymmetry in the $\gamma + p \rightarrow \eta' + p$ experiment planned at BGO-OD

Polarization observables in pseudo-scalar meson photoproduction have proved to be very efficient to fix parameters of resonances involved in the process [1,2,8,9].

In the case of $\eta'$ photoproduction off the proton, only total and differential cross section values are available in the literature (CLAS experiment at JLab [10, 11], and CB-ELSA-TAPS experiment at ELSA-Bonn [12]).

Two theoretical approaches were developed to describe these data [8,9]:

i) in a relativistic meson-exchange model of hadronic interactions [8], Nakayama and Haberzettl include mesonic t-channel ($\rho$ and $\omega$) together with nucleon s- and u-channel and resonances contributions. The included resonances were $S_{11}(1535)$, $P_{11}(1710)$, $D_{13}(1520)$ and $P_{13}(1720)$, the two latter being required to reproduce some details of the angular distribution;

ii) in a reggeized model for $\eta$ and $\eta'$ photoproduction [9], the above mentioned Authors used essentially the same ingredients but vector meson exchanges are treated in terms of Regge trajectories to comply with the correct high-energy behaviour.

Both approaches give a reasonable description of data and in both cases the authors stressed that the cross section data alone are insufficient to pin down the resonances.
Figure 10. Kinematics of the reaction $\gamma + p \rightarrow \eta' + p$. The curves show (25 MeV steps for the incident photon energy $E$) the behaviour of the proton laboratory angle $\theta_p$ as a function of the $\theta_{\eta'}$ center-of-mass angle.

parameters, while beam and/or target asymmetries could be very helpful to better determine the partial wave contributions in this reaction, and impose more stringent constraints on the parameter values.

BGO-OD shows an excellent detection efficiency for both neutral and charged final states and will provide a polarized photon beam, allowing for the determination of still unmeasured $\Sigma$ beam asymmetry in many reaction channels.

A very simple trigger is required to perform this measurement: the coincidence between a signal in the tagger and a constraint in the total energy collected by the BGO calorimeter, the latter is required to be greater than a threshold value $E_{BGO\text{-}thr}=180$-200 MeV. This simple trigger scheme proved to be very efficient in reducing the electromagnetic background (mainly pair production on the target cell and along the photon beam line) without affecting the hadronic count rate. In Figure 10 the kinematics of the reaction is displayed. We can see in this figure that, in our required conditions, the recoil proton will always be measured either in the dipole spectrometer, or in the MRPC position chambers. A complete measurement is thus feasible by detecting the recoil proton in the forward direction ($\theta_p < 25^\circ$) and the $\eta'$ decay products in the BGO calorimeter. We will detect the $\eta'$ via the following decay chains:

1. $\eta' \rightarrow \gamma \gamma$;
2. $\eta' \rightarrow \eta\pi^0\pi^0 \rightarrow 6\gamma$;
3. $\eta' \rightarrow \eta\pi^+\pi^- \rightarrow 2\gamma\pi^+\pi^-$. 
Figure 11. Event selection: the black curve is identical in left and central graphs and indicates the invariant mass spectrum of all events containing at least two photons measured in the BGO calorimeter, while in the right panel it indicates the missing mass from the detected forward proton. The red curve shows the same spectrum when exactly 2 photons (left), six photons (central), 2 photons and 2 identified charged pions (right) are reconstructed in the calorimeter. The blue curve shows the remaining events after the kinematical constraints from the recoil proton measurement are applied. In all cases (neutral and charged channels) the $\eta$ peak is cleanly selected.

For each decay chain the detection efficiency must be estimated. We have used a full MonteCarlo (MC) simulation of the detector setup that includes an event generator (updated version of the one described in [13]) containing all known hadronic cross sections off the proton as a function of the photon energy.

The result of the simulation and event selection procedure is summarized in Figure 11. In this figure we can see the yields (in arbitrary units) at various stages of the selection procedure: the black curve in all graphs represents the starting point of the event selection when at least 2 photons are detected in the BGO. In the neutral decay channel the main variable to identify the $\eta'$ events is the invariant mass reconstructed from the detected $\gamma$'s in BGO (left and central graphs in Figure 10), while in the charged decay the main variable is the missing mass to the detected and identified forward proton, because our apparatus is not able to directly measure the energy of charged pions in all solid angle (right panel in Figure 10). The red curve indicates the resulting spectrum when exactly 2$\gamma$ (left), 6$\gamma$ (central), 2$\gamma$ and 2 identified charged pions (right) are measured, and finally the blue curve shows the events that fulfil the kinematical constraints in the recoil proton measurement. The values of the reconstruction efficiencies depend on the percentage of background events that are accepted by the event selection procedure. By simulation, we estimate in accurate way that the analysis efficiency (taking into account the competition of all concurrent channels [13]) is about 25% for 2$\gamma$ channel, 4.4% for $\eta\pi^0\pi^0 \rightarrow 6\gamma$, and 5.4% for $\eta\pi^+\pi^- \rightarrow 2\gamma\pi^+\pi^-$. 

With the aim to measure the beam asymmetry from threshold up to 1.7 GeV with an error $\Delta\Sigma$ of 0.07 in five energy and six angular bins, we were able to estimate that
the experiment is feasible with the reasonable 1000 hours beam time, by using the 6 cm length liquid Hydrogen target and a photon beam linearly polarized through coherent bremsstrahlung with a total tagged intensity of \( N = 5 \times 10^7 \text{s}^{-1} \).

6. Conclusions

During the February/March beam time 2012, for the first time, tests on totally equalized and calibrated BGO detector were performed with a full equipped BGO electronics consisting of 30 ADCs AVM-16 Mambo from Wiener. The calibrated energy and time of energy deposits in the BGO crystals have been used in the analysis. No charged particle identification was available (no data from the plastic scintillator barrel or MWPC) and no data from the photon tagger or any information from the forward spectrometer was used in the analysis. The reconstruction of the pseudoscalar mesons \( \eta \) and \( \pi^0 \) from the decay photons was achieved. It was done plotting the two photon cluster invariant mass spectrum for events with at least 400 MeV energy deposit yields. It was performed an accurate feasibility study on the \( \gamma + p \rightarrow \eta' + p \) reaction, demonstrating the possibility to perform a \( \Sigma \) beam asymmetry measurement at BGO-OD experiment in the energy range starting from the threshold up to 1.7 GeV. We expect that the measure of this observable will be useful to contribute to solve the puzzle related to right weights of different resonances [8,9] involved in the reaction process, unsolved by the knowledge of the differential cross section [10–12].

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