Journal of Physics: Conference Series

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To cite this article: Andreas Neiser and (forthe A2 collaboration) 2015 *J. Phys.: Conf. Ser.* **587** 012041

Current Status and Performance of the Crystal Ball and TAPS Calorimeter

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Abstract. In the A2 experiment at the Mainz microtron (MAMI) electron accelerator, the production of nucleon resonances and light mesons off protons and nuclei using energy-tagged bremsstrahlung photons is studied. Decay products are measured with two electromagnetic calorimeters: Crystal Ball (CB), whose 672 NaI crystals cover almost the entire solid angle, and TAPS, which consists of 366 BaF2 and 72 $PbWO_4$ crystals in the forward direction. Here, we report on the current performance and status of both detectors after 10 years of operation in Mainz. In addition, we present the new CB high-voltage system, a new fast readout scheme for TAPS, and the planned upgrade of the CB data-acquisition system.

1. Introduction

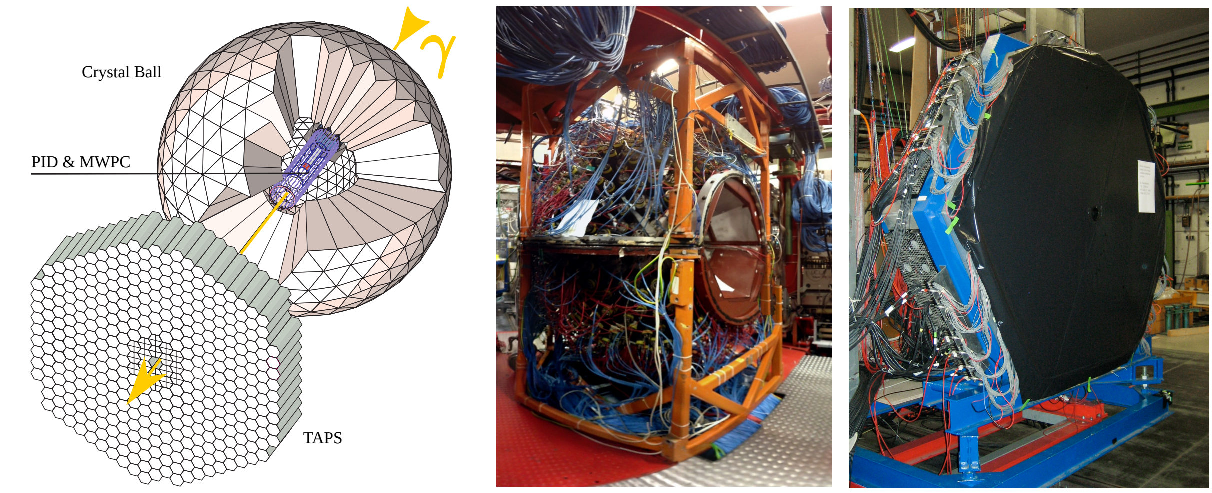
This contribution gives a short overview of the goals of the A2 collaboration in Mainz and the experimental setup to achieve them. Subsequently, it focuses on the two deployed calorimeters Crystal Ball and TAPS in corresponding sections, which have been in use for over a decade now at A2.

2. The A2 experiment at MAMI

The A2 collaboration investigates strongly interacting particles in the low-energy regime, where quantum chromodynamics as the underlying theory is not perturbatively solvable. Using energy-tagged bremsstrahlung photons, we currently study Compton scattering $\gamma p \to p\gamma$ to obtain the scalar and vector polarizabilities of protons [1]. Furthermore, we photo-produce mesons and investigate their their mainly uncharged decay channels to test effective field theories and to obtain information about the nucleon excitation spectrum, eventually leading to an unambiguous partial wave analysis [2].

MAMI is an electron accelerator located at the University of Mainz. It consists of four staged racetrack microtrons and provides a 100 % duty cycle electron beam. Maximum beam currents of 100 μA and 20 μA can be reached with unpolarized and 85 % polarized electrons, respectively. With three stages, energies from 180 to 883 MeV are available. Since 2007, a fourth stage provides 1604 MeV. Besides A2, the A1 collaboration uses the electron beam directly with excellent magnetic spectrometers.

A2 creates photons via the bremsstrahlung process off various radiators to obtain circularly and longitudinally polarized photons with the characteristic $1/\omega$ spectrum, where ω is the photon energy. The momentum of the post-bremsstrahlung electrons are determined in the Glasgow-Mainz electron tagging spectrometer [3]. It has 384 logical channels covering ω from 6 to 93 %



(a) (b) (c)

Figure 1. (a) The detector setup at the A2 experiment. The target is surrounded a the particle identification detector (PID), two multi-wire proportional chambers (MWPC) and the calorimeter Crystal Ball (some crystals intentionally not drawn). In forward direction, TAPS with its hexagonal modules is depicted. (b) and (c) show Crystal Ball and TAPS, respectively, inside the A2 experimental hall. For TAPS, the installed veto detectors (plastic scintillators) are visible, see text.

of the initial electron energy. The electron rate can be up to 1 MHz per channel, corresponding to a total photon flux after collimation of roughly $10^6 - 10^7$ Hz. Additionally, the electron beam polarization can be determined online via Moeller scattering by measuring both electrons in time coincidence. For the energy range $\omega \approx 1450 \ldots 1600$ MeV, which is largely not covered by the Glasgow-Mainz tagger, an end-point tagger is available since 2012 to study in particular the η' photo-production, which falls in this energy regime.

The photons impinge on different targets, most notably the "frozen spin" target providing longitudinally or transversely polarized nucleons [4]. It consists of radical-doped butanol beads cooled down to 20 mK with a ^{3}He/^{4}He dilution cryostat, allowing typical polarization degrees of 85 % with relaxation times of 2000 h. Additionally, liquid hydrogen or helium targets in thin containers with different lengths are typically used for unpolarized measurements with very low background.

In general, A2 is a fixed target experiment with full angular coverage aiming at a good two-photon invariant mass resolution,

$$m^2_{\gamma\gamma} = 2E_{\gamma 1}E_{\gamma 2}(1 - \cos\phi_{\gamma\gamma})\,, \tag{1}$$

in a large energy range from a few MeV to one GeV. Therefore, an excellent energy and angular resolution and a good particle identification is required. This is achieved with the two calorimeters Crystal Ball, covering 94 % of the solid angle, and TAPS in forward direction. It is complemented by two multi-wire proportional chambers for tracking and plastic scintillators for particle identification. See figure 1 for the general detector setup.

3. The NaI calorimeter Crystal Ball

The Crystal Ball NaI calorimeter was built in the mid-1970s for the e^+e^- collider SPEAR at SLAC for Charmonium spectroscopy. With this detector, the η_c was discovered. Later, it moved to DESY, and then in 1996 to BNL. Eventually, it was installed in Mainz in 2004 and equipped

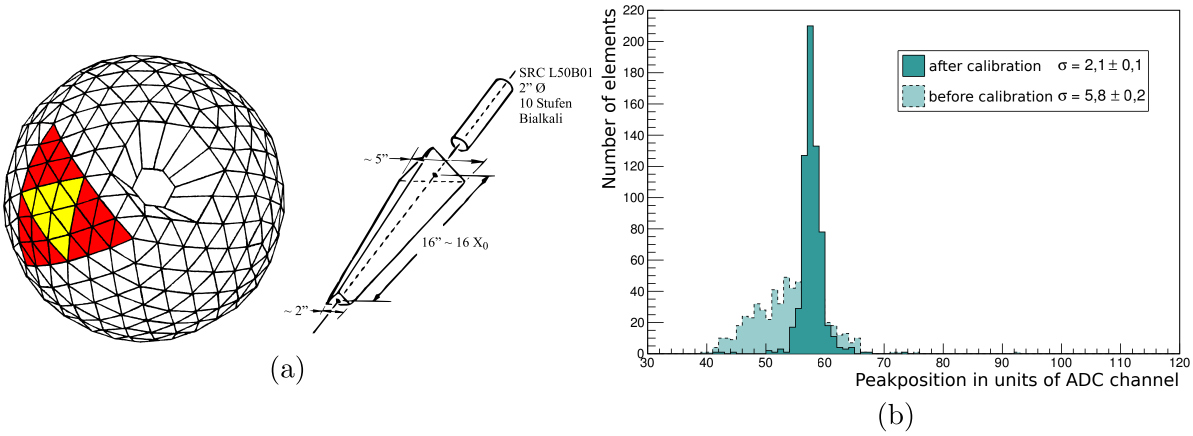


Figure 2. (a) The icosahedron geometry of the Crystal Ball, showing one colored major triangle, subdivided in four minor triangles. Additionally, one single NaI(Tl) crystal with its PMT is depicted [7]. (b) The distribution of Am/Be photopeak positions before (lighter color) and after (darker color) adjusting the PMT voltages of the Crystal Ball individually [9].

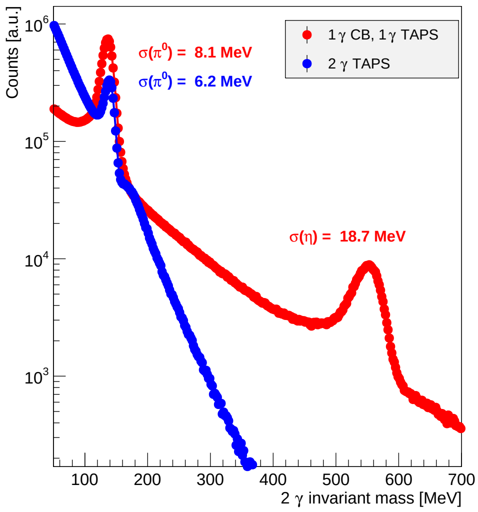
with new electronics [5]. ADCs with 40 MHz sampling rate are used to achieve a high dynamic range of > 400 and a good linearity in combination with TDCs with 117 ps ticks for timing. Thus, the data-acquisition system is not limiting the energy resolution of the Crystal Ball and, for example, the 4.4 MeV photons from ^{12}C, excited by incoherent π^0 photo-production, can be directly measured with sufficient resolution [6]. Since the rate is only limited by the VME cycle time of 1.5 μs, the number of VME CPUs on the Crystal Ball and tagger side were doubled during a major DAQ upgrade in October 2013. This increased the data acquisition rate by a factor of 2 to roughly 2 kHz under typical experimental conditions.

As shown in figure 2a, the Crystal Ball has an icosahedron geometry as major triangles, further divided into four minor triangles, which consist of 720 truncated pyramids in total. Excluding the beam entrance and exit holes, there are in total 672 Tl-doped NaI crystals, $15.7X_0$ long, still readout with the original PMTs [7]. They cover 94 % of the 4π solid angle. At 1 GeV, the energy resolution is about 1.7 %. The angular resolution is about 2.5° in polar and $2°/\sin\theta$ in azimuthal direction [8]. After over thirty years of operation, 8 channels are dead and 9 channels show bad ADC spectra. This is mostly due to insufficient light collection, but also due to three broken PMTs.

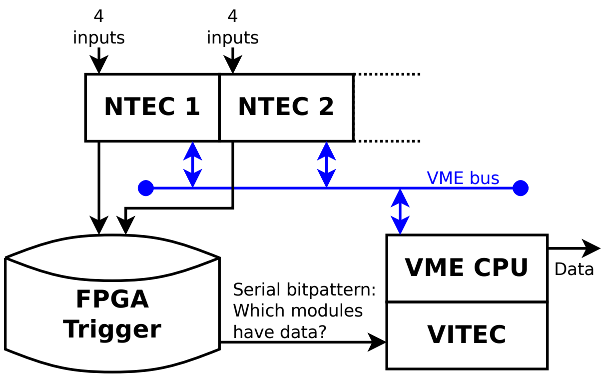
The electronics provide an analog sum of all PMT signals, being proportional to the total energy deposited in the Crystal Ball, which makes the calorimeter a self-triggering detector. Since 2012, there is a flexible FPGA-based trigger system yielding decisions on coplanarity and multiplicity of Crystal Ball clusters within a few hundred nanoseconds.

3.1. Hardware gain calibration

Owing to the very stable environmental conditions of the A2 experiment hall, a Crystal Ball gain calibration is only necessary every few years to achieve stable operation and thus trigger conditions concerning the already mentioned analog sum. To this end, an Am/Be radioactive source emitting 4.438 MeV photons is put in the center of the Crystal Ball and the PMT gain is adjusted such that the photon peak above an exponential neutron background is always located at the same position in the raw ADC spectrum. Previously, since the high voltage is provided by only four very stable supplies for all PMTs, each PMT gain was calibrated by manually adjusting variable resistor, which is a tedious procedure. In 2013, voltage regulator boards were developed in Mainz and replaced the simple distributor boards, allowing to set the PMT voltage



(a)



(b)

Figure 3. (a) The two photon invariant mass spectrum for one photon detected in Crystal Ball, one photon in TAPS (red), and for two photons detected in TAPS (blue). The observed peaks correspond to the decays of the uncharged pion and the eta, see text. (b) Schematic representation of the readout speed improvement by using trigger information, see text. The "New TAPS Electronics Card" (NTEC) is a CAEN V874 VME module with customized piggybacks.

individually but still using the very stable high-voltage supplies [9]. This cost-effective upgrade allows for a faster and more precise calibration method, see figure 2b, remotely controlled and monitored with EPICS [10]. The stability is roughly 0.3 V over 100 hours, corresponding to a negligible variation in measured energies of 0.02 MeV. After the calibration with the upgraded high-voltage system, π^0 peak widths of 8.6 MeV in the invariant two-gamma spectrum are measured, close to the resolution limit of the detector system, since offline analysis calibration does not reduce this width significantly.

3.2. Upgrade of the data-acquisition system

After one decade of operation, the data-acquisition system will be replaced by a readout system based on the TRB3 FPGA board, developed at the GSI, Darmstadt, for the HADES experiment [11]. This will increase performance further, but is also intended to sustain the maintainability of the system since spare parts for the current system are not available anymore. In the far future, the TRB3, as a flexible $4 + 1$ FPGA board with customizable piggybacks, can also be part of a hardware-triggerless data acquisition, allowing multiple experiments at the same time. Up to now, first tests with different front-ends have been carried out. The main challenge is the large energy range of $1 \ldots 400$ MeV of the NaI signals. Additionally, the A2 collaboration profits from the large TRB3 user base, including the collaborations PANDA and MUSE, providing auxiliary software, documentation and debugging [12].

4. The BaF_2 and $PbWO_4$ calorimeter TAPS

The "Two-Arm Photon Spectrometer" TAPS is a BaF_2 calorimeter consisting of hexagonal modules, which can be arranged in different configurations tailored to various experiments.

Since 1988, the number of modules increased from 190 to 600 in 2006. Then, the detector was split and 384 modules were installed in Mainz and 216 in Bonn, both as forward wall detectors. In 2001, plastic scintillators in front of each module were installed as a charged particle veto system, and in 2004 a new readout system was commissioned [13]. In 2007, the modules of the two inner rings were replaced by 72 $PbWO_4$ crystals in Mainz to cope with higher hit rates in the very forward region.

In Mainz, the detector covers the important forward region $\theta = 0° \dots 20°$. The BaF_2 crystals are $12X_0$ long, and the inner $PbWO_4$ $17X_0$. In addition to the veto detectors, photons and protons can be separated by a pulse shape analysis of the BaF_2 scintillation light. This is reflected in the electronics by integration gates of different lengths. The energy resolution is 2 % at 1 GeV with all 366 BaF_2 crystals working and stable. The $PbWO_4$ crystals are operated at room temperature, and their calibration is more difficult due to large backgrounds. Currently, 6 modules have a broken PMT and another 8 show bad ADC spectra. However, they become increasingly important for the upcoming η' measurements with the end-point tagger in 2014 since most of the outgoing protons will be scattered into the very forward region. Hence, the 6 currently broken $PbWO_4$ modules will be replaced in June 2014 and the reason for the 9 bad spectra will be investigated.

In figure 3a, the overall performance of the calorimeter system is demonstrated with the inclusive reaction $\gamma p \to X\gamma\gamma$, where the analysis identified the photons as uncharged clusters with no further cuts applied. The initial electron energy was 1557 MeV, and liquid deuterium was used as a target. Although there is a significant amount of combinatorial background, signals from the decays $\pi^0 \to \gamma\gamma$ and $\eta \to \gamma\gamma$ can be nicely identified.

During the hardware upgrade in October 2013, each VME CPU was additionally equipped with a multi-purpose I/O card, the VITEC, which received the serialized event number and handles the readout synchronization between VME crates. It was measured that the TAPS VME readout system was the bottleneck after the upgrading the Crystal Ball and tagger systems. Since the VITEC was developed in Mainz, its FPGA was easily reprogrammed such that it receives a bit pattern from the TAPS FPGA-based trigger subsystem, enabling a fast pedestal suppression on the VME CPU by skipping empty modules, see figure 3b. Since the hits over the whole TAPS system are typically sparse, this improved the readout time by a factor of 3 from 176 μs to 56 μs.

5. Conclusion

In summary, both calorimeters Crystal Ball and TAPS showed stable operation and excellent performance during the various tagged photon experiments carried out at A2. In the next years, upgrading the Crystal Ball and tagger hardware is a major task to ensure maintainability and improve performance. Moreover, the performance of TAPS can be increased even further by splitting its VME crates similar to the Crystal Ball and tagger crates.

Acknowledgments

A.N. receives a Fellowship through GRK Symmetry Breaking (DFG/GRK 1581).

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