JNPS

ISSN 2392-473X
Journal of Nepal Physical Society, August-2015, Vol. 3, No. 1

Experimental Facility at A2 Collaboration (MAINZ) for Photoproduction reaction

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Abstract

Since 20 years, a very successful experimental program with real photons has been achieved at the Mainz Microtron (MAMI) facility.The A2 Collaboration at MAINZ is a unique place for the experimental facility of photoproduction reaction. The combination of highly sensitive photo spectrometers Crystal Ball and TAPS as forward wall detector along with particle identification detector and Multiwire proportional chambers as inner wall detectors provide the high precision of the measurement. MAMI-C, which consists of there Race Track Microtrons (RTMs) with the Harmonic Double -Sided Microtron (HDSM) is an intense, stable and continuous-wave accelerator to accelerate electron to 1.5 GeV. This electron beam is responsible to produce real photons via bremsstrahlung process at Glasgow Photon Tagger. A major part of the ongoing and future programme at MAMI will exploit polarised nucleon targets.

Keywords: *Mainz microtron, the glasgow photon tagger, crystal ball, the taps detector, multiwire proportional chambers, particle identification detector.*

1. Introduction

The main purpose of the A2 Collaboration in Mainz, Germany, is to plan, realize, run and analyze high precision nuclear experiments with real photons at MAMI in the photon-energy range between 40 MeV and 1603 MeV. Monochromatic photons via a bremsstrahlung process are used for all experiments. Polarized photon beams, linear and circular, are available as well as polarized targets. Groups from several institutions and countries have provided different detector components like the photon spectrometer TAPS , PID, photon tagger and more recent the photon spectrometer Crystal Ball (e.g., *Beck,* 2006). A very successful experimental program with real photons has been achieved in 20 years of operation at the Mainz Microtron (MAMI) facility. Many data have been taken on the proton, deutron and on light and complex nuclei for the exploitation of the total photon absorption, compton scattering, meson production, break up reactions and multi pion, eta and strangeness photo production in the final state. The coupling of an intense photon beam and close to complete detector acceptance offers unique opportunities for precision measurements to challenge our understanding of the structure of the nucleon and the nucleus as well as the underlying theory of Quantum Chromo Dynamics (QCD) [e.g., *Watts,* 2011]

2. Experimental Set-Up

The set-up is mainly comprised of the three components shown in Fig. 1. The primary component is the electron accelerator, which is also called the Mainz Microtron (MAMI-C). It produces a continuous-wave electron beam. The beam of electrons from MAMI-C is directed onto a thin diamond or copper foil generating a beam of high-energy photons via a bremsstrahlung process. The second component is the Glasgow Photon Tagging Spectrometer, which is used to analyze the momentum of the corresponding bremsstrahlung electrons. The photon beam is allowed to impinge on a target causing the production of various particles. The third component, which is the detector system used to detect these particles and their decays, consists of the Crystal Ball (CB) and the TAPS spectrometer, Particle Identification Detector (PID) and Multi wire propotional chambers (MWPC).

Mainz Microtron (MAMI)

The Mainz Microtron (MAMI) is an intense, stable and continuous-wave accelerator that accelerates electrons to the relativistic limit. It is operated by the Institut fur Kernphysik at Johannes Guttenberg Universitat in Mainz, Germany. The accelerator in its current configuration was constructed in four stages: (i) MAMI-A1, (ii) MAMI-A2, (iii) MAMI-B, and (iv) MAMI-C. MAMI-A1 was installed in 1979, producing electrons up to 14 MeV. In 1983, a second microtron was added, upgrading the facility to MAMI-A2 with maximum energy 183 MeV. With the addition of a third microtron in 1990, the maximumenergy was increased to 855 MeV under the name MAMI-B.

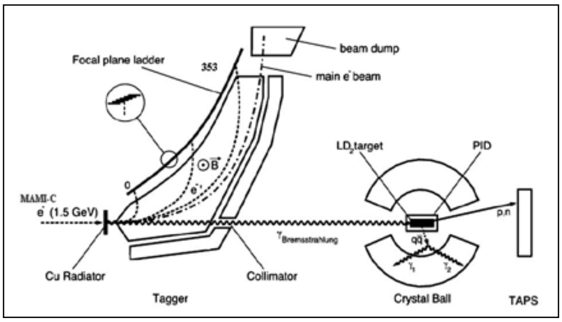

Figure 1. The experimental set-up in the A2 Hall in Mainz consists of three main components: (i)MAMI electron accelerator for production of electrons up to 1.5 GeV, (ii) Glasgow Photon Tagger, (iii) Detector system (CB, TAPS, PID, MWPC).

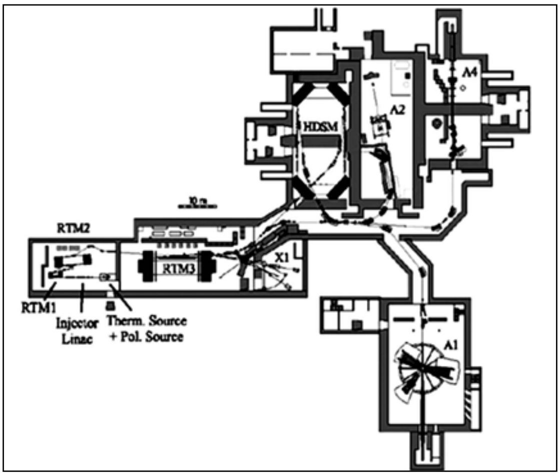

Figure 2. The floor plan of MAMI facility.

MAMI-C, which is the present facility, was set into operation in December, 2006 producing a continuous high quality electron beam with maximum energy 1.5 GeV. It supplies the electron beam to any of the experimental halls (A1, A2, A4, X1) as shown in Fig. 2.

Three racetrack microtrons RTM1, RTM2, and RTM3 together with the Harmonic Double Sided Microtron (HDSM) produce an electron beam with energy up to 1508 MeV in MAMI-C. A1, A2, A4, and X1 are the experimental halls. MAMI-C consists of three cascades of RTMs (Race Track Microtrons) and a recently added Harmonic Double-Sided Microtron (HDSM).

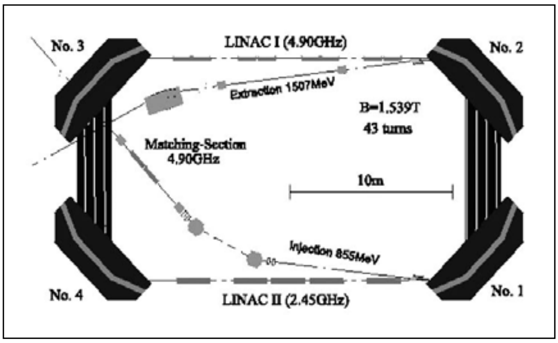

Figure 3. General layout of the HDSM.

This new HDSM is considered as a worldwide unique recirculating electron accelerator. It consists of two systematic pairs of 90°-dipoles, each forming an achromatic 180° bending system as shown in Fig. 3. In order to compensate for the strong vertical defocusing due to the 45°-pole face inclination at beam entrance and exit, these dipoles incorporate an appropriate field gradient normal to the pole edge. This functions as a scheme for transversal focusing, with only two quadrupole doublets on each of the two dispersion-free anti-parallel linac axes. In the HDSM, the two linacs operate at different frequencies: one at 2.45 GHz and the other at 4.90 GHz. The linac operating at the lower frequency maintains a higher longitudinal stability. The linac at the higher frequency is responsible for a synchronous acceleration energy gain per turn below 20 MeV [*Jankowiak et al.,* 2006]. For the HDSM, the electron energy gained per turn is given by;

$$\Delta E / turn = n \times ecB\,(\pi - 2) \times \lambda_r f \qquad (1)$$

with the value of B = 1.23 T, λrf = 0.1224 m; thus, from Eq. (1), ΔE = 41.1 MeV/turn. This also needs 20 m long linacs, which would not fit into the existing MAMI-floor, as shown in Fig. 3 . Moreover, it would consume four times the electric power of MAMI-B. So it is practicable to adjust the frequency of the HDSM at 4.90 GHz (λrf = 0.0612 m) with a small variation in B value as 1.823 T, to keep the length of the linacs about 10 m and the other parameters similar to that of RTM3.

HDSM consists mainly of two pairs of 90° bending magnets and two linear accelerators. These two linear accelerators work on two different frequencies, 2.45 GHz and 4.90 GHz. Figure from Ref. [*Jankowiak et al.,* 2002].

The HDSM takes the beam energy from 855 MeV to 1508 MeV by 43 turns in 14.0 to 16.7 MeV per step through its accelerating section.

The Glasgow Photon Tagger

The Glasgow Photon Tagger was installed in the A2 Hall in 1991 for MAMI-B with a maximum electron energy of 883 MeV. Recently the Tagger was upgraded for the MAMI-C accelerator to work up to maximum electron energy of 1508 MeV. The electron beam from MAMI-C is made to collide with a thin diamond or copper radiator of the Glasgow Tagger, to produce photons through the bremsstrahlung process:

$$e^- + A \rightarrow A + e^- + \gamma$$

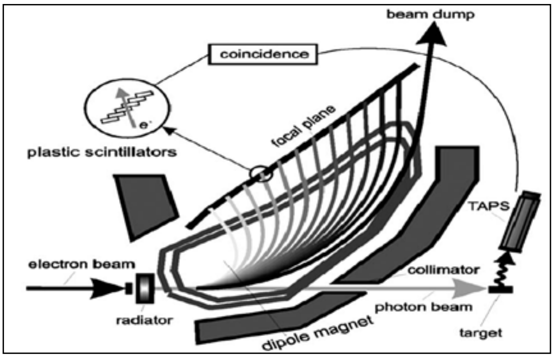

Figure 4.The Glasgow Tagger.

where$e-$is an electron, A is a nucleus, and γ represents a photon.

As soon as the high-energy electron beam strikes the surface of the radiator, photons are created by the bremsstrahlung process. The trajectory of the electrons is bent by a huge Tagger dipole magnet onto the focal-plane detectors and the photons are sent to the target. Using the principle of conservation of energy and momentum, the photon energy is given by;

$$E_\gamma = E_0 - E_e \qquad (2)$$

where ***E0*** is the electron beam energy and ***Ee*** is the energy of the deflected electron. In this equation, the recoil energy of the nucleus has been ignored due to the large mass of the nucleus compared with the energy of the photon and electron. In order for the application of Eq. (2), the timing coincidence of each photon to the corresponding electron should be known. This process of using the timing coincidence to match an electron to its corresponding photon is called tagging. The Glasgow Photon Tagger used for the tagging process is shown schematically in Fig. 4. It consists of 353 plastic scintilla tors that overlap each other to form a ladder in the focal plane of a quadrupole magnet of weight 1030 tons, which produces a magnetic field of 1.8 T. These focal-plane detectors have a length of 8 cm, a thickness of 0.2 cm, and widths of 0.9 to 3.2 cm. They cover an energy range from 6-95% of the energy of the primary electron beam. The different widths of these detectors are arranged in such a way as to achieve slightly more than half-overlap of neighboring detectors so that each tagging electron should trigger two detectors at a time. The width of the overlap region (a "channel") is equivalent to an energy width of 4 MeV for an incident electron beam energy of 1500 MeV, and neighboring channels overlap by about 0.4 MeV [*McGeorge et al.,* 2008]. All the events involving only a single detector are rejected, which thereby reduces the background. Each detector is adjusted perpendicular to the anticipated electron's path for the electron momentum corresponding to that particular position in the focal-length plane. During the construction of the Tagger, the number of required focal-plane R. Novotnydetectors was determined by the physical space occupied by a single photomultiplier. The 353 detectors provide a maximum comfortable packing density for the photomultiplier tubes, covering an electron range of 80 to 1401 MeV with photon flux up to 2.5×10^5 photons per MeV and an energy resolution of about 4 MeV. Most of the electrons in the incident beam do not interact with the radiator and are deflected by the magnet onto a Faraday cup called the beam dump. A collimator consisting of four lead cylinders each 2 cm long with a 4 mm hole bored through the center parallel to the beam axis is used to eliminate the noise and deviations of the resulting photon beam. Thus because of the use of the collimator, the ratio of the photons to the electrons is always less than one. This ratio is calledthe tagging efficiency:

$$\varepsilon = N_\gamma / N_e \qquad (3)$$

where *N*γ is the number of photons that passed through the collimator and *Ne* is the number of electrons detected in the tagger ladder. The tagging efficiency is measured by using a Pb-glass detector placed downstream of the collimator in the beam line to measure

$N\gamma$. While performing the tagging efficiency measurement, normal experimental beam currents may damage the lead-glass detector. Therefore, a greatly reduced beam current was used to protect the lead-glass detector. The photon beam was monitored with an ionization chamber that measures the overall bremsstrahlung flux during normal running.

As the bremsstrahlung spectrum is a continuous one in which the photon flux varies as $N_\gamma \sim 1/E_\gamma$, a larger number of low-energy photons is produced that are accompanied by the high-energy photons. For our experiment, the high-electron energy (low-photon energy) area of the Tagger focal plane was switched off so that the energies of the tagged photons varied from 700 MeV to 1400 MeV.

The Crystal Ball

The Crystal Ball (CB) was designed in 1974 as a multi photon spectrometer with high detection efficiency over a large solid angle. It was initially used to detect photons produced in high-energy *e- e+* collisions [e.g., *Bloom and Peck,* 1983] at SLAC (Stanford Linear Accelerator Center in Stanford, CA). From 1978 to 1981, it was used to investigate the spectroscopy of the J/Ψ and radiative decays of particles such as τ , Ψ, and *D*at Stanford Positron Electron Accelerating Ring (SPEAR). After this period, it was put into storage at SLAC until 1995 when it was moved to the Alternating Gradient Synchrotron (AGS) facility at BNL, where it was used for the study of nucleon and hyperon spectroscopy, and rare ηdecays. It was moved to Mainz in 2002 and after completion of a major upgrade of the detector's electronics it was used at MAMI-B until 2005. It resumed operation in 2007 as the central detector at MAMI-C. The CB consists of 672 thallium-doped sodium iodide NaI (Tl) crystals. These crystals are optically isolated from one another by wrapping them in reflecting paper and aluminized mylar. A SRC L50B01 type photomultiplier tube (PMT) of 5.1 cm diameter and 21 cm in length is arranged behind each crystal to convert the resulting light pulse into electric signals. Each crystal is shaped like a truncated pyramid of length 40.6 cm (or 15.7 radiation lengths) with the side of inner face 5.1 cm in length andthe side of outer face 12.7 cm.

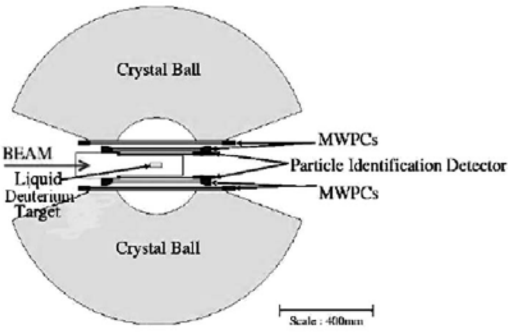

Figure 5. A transverse view of the Crystal Ball showing the sub detectors inside it. A liquid deuterium target is also located at its center.

These crystals are arranged to form a ball structure as shown in Fig. 5 with an inner radius of 25.3 cm and outer radius of 66 cm. The geometry of the Crystal Ball is that of an icosahedron (a solid with 20 faces). These 20 faces form "major triangles" which in turn are divided into faces of four "minor triangles" each containing nine crystals. When these crystals are stacked together closely they form a spherical shell of 720 elements. In order to make a space for the photon beam and the target system, 24 crystals were removed from the opposite poles.

The CB is divided into two hemispheres: an upper one and a lower one separated with two 0.8 mm stainless steel plates and a 0.8 cm air gap. Because of this, an active space amounting to 1.6% of the solid angle (or 4π) is introduced. Since NaI(Tl) is hygroscopic, all the crystals are hermetically sealed in the two separated hemispheres. This also helps to control the temperature (_23±2◦C), pressure (low) and humidity (30%) inside the hemispheres.

In the Crystal Ball, the incident photon beam produces electromagnetic showers that in turn deposit their energy in the NaI(Tl) crystals depending on the energy of the photon. An incident photon below 10 MeV may deposit energy only in one or two crystals whereas a photon up to 400 MeV deposits 98% of its energy in a cluster of 13 crystals. Because of this, the measurement of photon energy from the Crystal Ball is considered quite precise and the energy resolution is taken as

$$\sigma_E / E = 2.0\ \% / E(GeV)^{0.36} \qquad (4)$$

Because of the high granularity of the Crystal Ball it also has a good position resolution. For hadrons and charged particles, the positional resolution is not optimal as the hadronic shower has less transverse extension. Thus for charged particles other additional detectors are required.

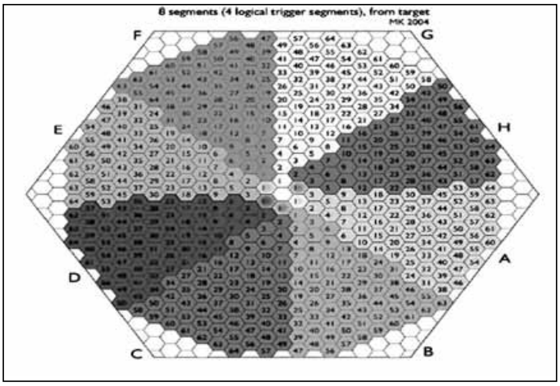

Figure 6. Individual TAPS BaF**2** detector consists of a hexagonally shaped crystal tube of 25 cm in length.

The TAPS detector

TAPS is a front-end detector for the Crystal Ball as it detects photons or any charged particles that escape from the exit hole of the ball. TAPS was designed and installed with the purpose to study high-energy photon beams as well as neutral mesons [*Novotny,* 1991].

TAPS consists of several hundred hexagonally shaped BaF**2** detectors (see Fig. 7) each of length 25 cm (equivalent to 12 radiation lengths) that can be arranged in different configurations. For our experiment, 384 BaF**2** crystals were configured as a forward wall at a distance 180 cm from the center of the Crystal Ball covering the angular range 0◦ < θ <20◦. The combined photon detection set-up for the Crystal Ball and TAPS shown in Fig. 7, covers approximately 96% of a complete sphere.

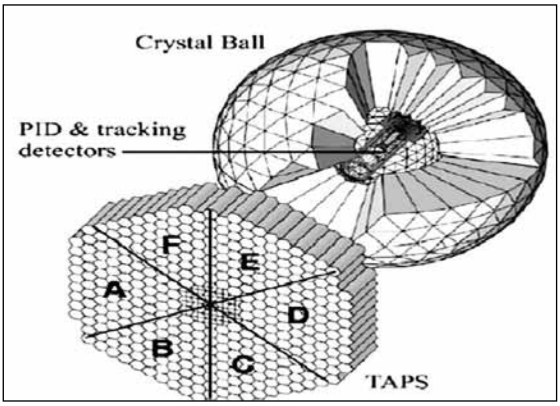

Figure 7. The use of TAPS as a forward wall detector at a distance 1.8 m from the CB which covers the hole of the CB to cover 96% of 4π in solid angle.

Since many particles are emitted in the forward direction, this forward wall is useful to increase the overall detection efficiency. Each of the BaF2 detectors has hexagonal front and back shapes with a cylindrical end part of inner diameter 5.9 cm as shown in Fig. 3.10. The surfaces of the crystals are polished. A UV reflector that is made up of eight layers of Polytetrafluorethylene (PTFE) and one layer of thin aluminum foil is wrapped around these crystals. The individual crystals are coupled to a Hamamatsu R2059 photomultiplier tube using silicone grease. In order to provide effective magnetic shielding up to a flux of 0.02T, the phototubes and the cylindrical section of the crystals are completely surrounded by a magnetic shield. In front of each BaF2 detector, a hexagonally shaped 5 mm thick NE102A plastic scintillator is installed so as to distinguish between charged and neutral particles. These are called veto detectors.

Particle Identification Detector (PID)

The PID shown in Fig. 8 is a cylindrical detector with 10 cm inner diameter around the beam axis centered on the target within the Crystal Ball. It is comprised of 24 plastic scintillators each with the size 31 cm × 1.3 cm × 0.2 cm. Optical isolation between each scintillator is achieved by by wrapping each individually in a foil. Each of these scintillators is connected to a Hamamatsu R1635 photomultiplier tube of thickness 10 mm.

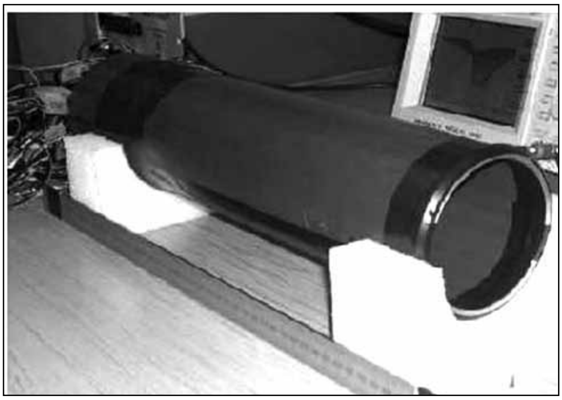

Figure 8. The PID before inserting it into position within the CB.

The PID is installed inside the Crystal Ball for the identifying charged particles. This detector measures small energy losses (ΔE) in the thin plastic scintillators and a rough variation of the azimuthal angle (φ) of the charged particles. By considering this ΔE and the total energy deposited in the Crystal Ball one can identify different charged particles. In our experiment we did not use the output of PID because our analysis involved only neutral particles.

Multiwire proportional chambers (MWPCs)

There is a charged-particle tracking detector inside the Crystal Ball that surrounds the PID and consists of two cylindrical multiwire proportional chambers (MWPCs), as shown in Fig. 9. Each MWPC has three layers: an inner and outer layer that act as a cathode and a

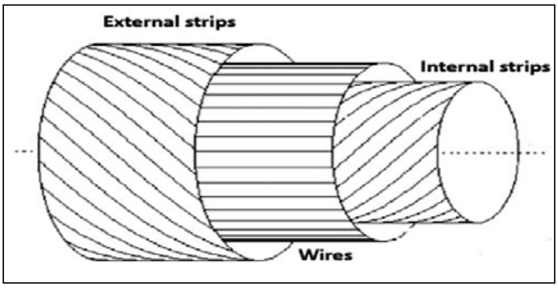

Figure 9. Multi Wire Proportional Chamber(MWPC) diagram showing relative positions of anode wires and cathode winding.

middle layer that acts as an anode. The cathode layers are made of 1 m Rohacel covered with 25 μmKapton film and the anode layer is an array of thin diameter tungsten wire stretched parallel to the cylindrical axis at 2 mm intervals around the circumference [*Albert,* 2003].

The cathode layers are wound helically in opposite directions at an angle of ±45◦ with respect to the wires. A mixture of argon (74.5%), ethane (25%), and freon (0.5%) is filled between the gap (4 mm) of the anode and cathode layers. A high positive voltage of 2300-2500 V is applied between the anode wire and the two cathode layers. The MWPCs cover the complete azimuthal angular range and 21◦ to 159◦ in the polar angular range. During the measurements for this work these chambers were turned off. This was of little importance since our analysis involved only the detection of neutral final-state particles.

Mainz/Dubnapolarised target

The polarized Frozen-Spin target was constructed and operated in close cooperation with the Joint Institute for Nuclear Research in Dubna, Russia. The establishment of target was completed in 2010. The new Frozen-Spin target was designed to retain the high angular acceptance of the detector system. A new target system containing nucleons with a high degree of longitudinal or transvers polarisation has been developed [e.g., *Watts,* 2011].

The main boundary condition for the outer diameter of the target cryostat was the most inner particle identification detector PID2 with a diameter of 104 mm. The internal holding coils had to be as thin as possible to allow particles to punch through. The core of the Frozen-Spin target for the Crystal Ball detector is a specially designed, large, roughly 2m long, horizontal **3**He/**4**He dilution refrigerator as shown in Fig. 10.

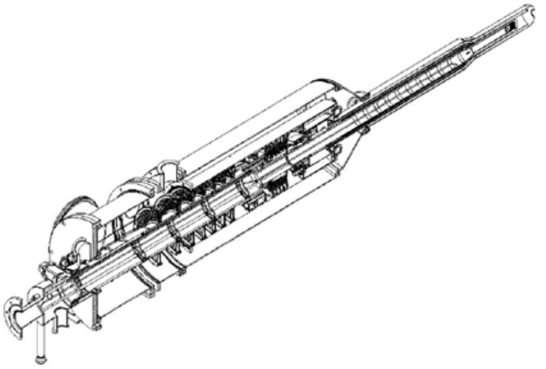

Figure 10. The 3Helium-4Helium dilution refrigerator.

In the frozen spin technique the target material (butanol) is doped with small quantity of material producing free radicals. The electrons in the doped material are then highly polarised by cooling the target to milli Kelvin and placing it within a strong polarizing field of 5 Tesla. The beam axis is equal to the cryostat axis and the target material has to be loaded along the beam axis using a specially adapted, twofold target-insert. This target-insert needs to seal the cavity against the beam pipe vacuum. The cryostat could provide a very low operation temperature of 25mK in the target chamber. The butanol is filled into a PTFE-cylinder of 2cm length and diameter.

Once the electrons are highly polarised their polarisation is transferred to the nucleons via Dynamic Nuclear Polarisation. In this process the transfer of spin is facilitated by exposing the target material to microwaves. Once the spin is transferred the polarisation of the target is maintained by a smaller holding field provided by a superconducting coil placed around the target. During operation the target had a typical relaxation time of 1000 hours. The maximum polarisation for protons is 90%. In the future the target will also operate with polarised deuterons from deuterated alcohol target material.

3. Conclusion

The photo spectrometers Crystal Ball and TAPS along with other detectors (PID and MWPC) coupled with the intense tagged photon beam at MAMI has high precision of measurement at A2 collaboration, which provides an excellent facility to carry out investigation of photo production reactions for the further understanding of the structure of the nucleon, the nucleus and the underlying properties of Quantum Chromo Dynamics(QCD).

Acknowledgments

Author would like to thank all the members of the Crystal Ball at MAMI, TAPS, and A2 Collaboration.

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