Letter of Intent for an Experiment

"Measurement of Nucleon Polarizabilities with an Active Time Projection Chamber at MESA"

Spokespersons for the experiment:
E. Maev (Petersburg Institute of Nuclear Physics, Gatchina, Russia)
P. P. Martel (Institute for Nuclear Physics, JGU Mainz, Germany and Mount Allison University, Sackville, NB, Canada)
V. Sokhoyan (Institute for Nuclear Physics, JGU Mainz, Germany)

Abstract

We propose to perform a set of experiments to extend the world data set for elastic Compton scattering with the goal to precisely extract the nucleon (proton, neutron) scalar polarizabilities, $\alpha_{p,n}$ and $\beta_{p,n}$. Using photons with energies of 20 – 100 MeV, we propose to measure the energy dependence of the differential cross-section $d\sigma(E_\gamma,\theta_\gamma)/d\Omega$ for Compton scattering of photons on protons, deuterons or helium nuclei using an active Time Projection Chamber (TPC). The experimental setup will allow detection of recoil particles in combination with the scattered photons. The detection of the recoil particles (proton deuteron, helium ions) will be achieved taking advantage of a high-pressure TPC, serving as an active target. The experiments can be performed at the MESA accelerator with an untagged photon beam. We are also exploring the opportunities for measuring nucleon polarizabilities with a tagged photon beam by combining the Crystal Ball/TAPS setup at MAMI with a new TPC serving as an active target for detection of low energy recoil particles (to be presented in future proposals).

1. Introduction

The electric and magnetic scalar polarizabilities characterize the response of the nucleon to external electric and magnetic fields and are fundamental properties of the nucleon, such as the radius, charge, and magnetic moment. The nucleon polarizabilities can be accessed by measuring cross sections or asymmetries for Compton scattering on the nucleon as a function of photon energy and scattering angle with subsequent fits of the experimental data using theoretical models. The proposed precise experimental measurements of $d\sigma(E_\gamma,\theta_\gamma)/d\Omega$ with focus on the photon energies below the pion photoproduction threshold (20 – 100 MeV) can be performed at the MESA accelerator in Mainz.

The main ideas and motivation to measure the proton scalar polarizabilities has already been presented to the PAC 2012 (pilot experiment) [1] and PAC 2016 (high-precision data) [2]. Both proposals focused on measurements of the proton polarizabilities with the A2 setup at MAMI and were rated with A by MAMI PAC. The results of the test run performed by the A2 Collaboration, where the beam asymmetry Σ_3 was measured for the first time below pion photoproduction threshold

[3] allowed to understand the systematics of such experiments. In the second set of experimental runs, the unpolarized cross section and beam asymmetry Σ_3 were measured with unprecedented precision (analysis is close to be completed) [4]. Moreover, a proposal for measuring neutron polarizabilities with an active helium target utilizing scintillation light (also in combination with the Crystal Ball/TAPS setup) was previously presented to MAMI PAC [5] and was rated with A as well.

The present LOI utilizes the same physics motivation to measure the nucleon (both neutron and proton) scalar polarizabilities α_{E1} and β_{M1}. The main goals are to achieve high precision in the determination of the neutron polarizabilities and to provide complementary results for the proton scalar polarizabilities using Compton scattering at low photon energies (20 – 100 MeV). The main difference compared to the previous experiments is that the low-energy recoil particles (proton, deuteron, or helium isotopes) are detected in an active TPC allowing us to determine the energy of the recoil particles with high accuracy. The scattered photons can be detected using NaI crystals placed outside of the TPC. This allows for a new and complementary approach to the measurement of the Compton scattering on nucleons with a detection of both particles in the final state.

2. Current Experimental Results

2.1. Proton polarizabilities

The current PDG values (based on previously existing data without new A2 results) for the polarizabilities of the proton are:

$\alpha_p = (11.2 \pm 0.4)\times 10^{-4}$ fm^3 and $\beta_p = (2.5 \pm 0.5)\times 10^{-4}$ fm^3 [6][1].

Previously, the proton scalar polarizabilites were extracted from the unpolarized cross section of Compton scattering on the proton at low energies (see, e.g. Refs. [7-9]). The largest of the data sets for Compton scattering was previously obtained with the TAPS setup at MAMI [9]. Recently, the A2 Collaboration acquired new data sets on Compton scattering for the photon energy range 80 – 140 MeV, measured the unpolarized cross section for Compton scattering with unprecedented precision and performed the first ever measurement of the beam asymmetry Σ_3 below pion production threshold [3,4]. Figure 1 shows the existing data in the low energy range and an example energy bin from the preliminary results on the unpolarized cross section from the A2 Collaboration.

In the experiment proposed in this LOI, we plan to cover photon beam energies from 20 MeV to 100 MeV. The coverage of the lower energy range (e.g. below 50 MeV) allows access to the terms which are practically not affected by the contribution of scalar polarizabilities and can be used as an input for verification of results obtained at higher energies closer to 100 MeV where the contribution of scalar polarizabilties increases. These measurements will also be used as a reference (and cross check of systematics) for the new measurements of neutron polarizabilties with deuteron and helium targets which will also be performed with an active TPC.

[1] All polarizabilities will be given in the text in units of 10^{-4} fm^3.

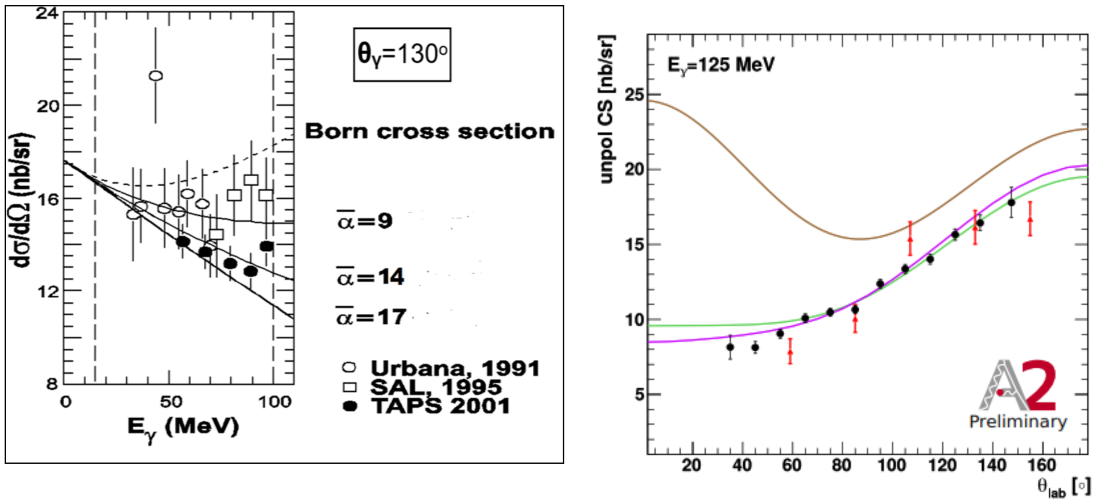

Fig. 1. *Left panel:* Differential cross sections for Compton scattering on the proton at $E_\gamma < 100$ MeV obtained in the experiments at Urbana [7], SAL [8] and Mainz (TAPS) [9] at an angle $\theta_\gamma \sim 130^o$. The solid lines correspond to calculations for different values of α using the LET formula ($\alpha_p + \beta_p = 14.2$). The dashed line corresponds to calculations of the cross section for the point-like proton. *Right panel:* Preliminary unpolarized cross section from A2 (black circles) [4], compared to the previous results from Ref. [8] (red triangles). The curves correspond to the Born contribution (brown), Dispersion Relation calculation (magenta) [10, 11], and heavy baryon ChPT calculation (green) [12]. The Dispersion Relation and heavy baryon ChPT calculations were performed for $\alpha_p = 10.65\times10^{-4}$ fm^3 and $\beta_p = 3.15\times10^{-4}$ fm^3.

2.2. Neutron polarizabilities (α_n and β_n)

The main focus of the future measurements will be on the improvement of rather poorly known polarizabilities of the neutron. Presently, the values of the neutron polarizabilties are

$$\alpha_n = (11.8 \pm 1.1)\times10^{-4}\ \text{fm}^3 \text{ and } \beta_n = (3.7 \pm 1.2)\times10^{-4}\ \text{fm}^3 \text{ [6].}$$

Despite a significant improvement within last years, the relative errors are still larger compared to the ones for the proton polarizabilities by almost a factor of 3.

The elastic Compton scattering from the deuteron (γd) offers a relatively unrealized opportunity for extracting the neutron polarizabilities. Here the coherence of both neutron and proton amplitudes leads to a significant advantage. Namely, the $O(E_\gamma^2)$ contribution of the neutron polarizability interferes with the $O(1)$ contribution of the proton's Thompson amplitude, thus strongly enhancing the neutron polarizability contribution to the cross section. Further, the contribution from the t-channel π^0 exchange diagram is isospin forbidden in γd scattering. As a result, the nucleon spin polarizability – which derives largely from this source, and is already an $O(E_\gamma^4)$ correction – is further suppressed. Of course, it is still necessary to carefully account for two-body currents when interpreting the data. Both meson-exchange currents and meson-exchange seagulls are potentially important and must be evaluated.

One relatively minor complication in interpreting the γd elastic data derives from the fact that the experiments are sensitive only to the isospin-averaged combinations:

$$\alpha_N = (\alpha_p + \alpha_n)/2 \text{ and } \beta_N = (\beta_p + \beta_n)/2.$$

However, given the accuracy with which both α_p and β_p have been previously determined, the extraction of α_n and β_n is both straightforward and potentially quite precise. The deuteron Compton scattering ($\gamma d \rightarrow \gamma d$) experiments were carried out at Illinois [13], SAL (Saskatoon) [14] and Lund [15,16] with photon energy from 49 to 115 MeV. The world database of deuteron Compton scattering is much smaller and is of poorer quality than that for proton and new precise data are highly desired.

Another opportunity provided by our setup is related to measuring Compton scattering on helium isotopes for accessing the neutron scalar polarizabilities. There are no Compton scattering data available for ^{3}He, while published data exist for ^{4}He in the energy range 60 - 90 MeV (see e.g. Refs. [17,18]) but there is still significant room for improvement. Another new data set acquired in 2019 by the A2 Collaboration at MAMI at energies from 65 MeV up to pion photoproduction threshold (with a detection of scattered photon) is presently under analysis.

3. Planned Experiments

3.1. Experimental method

In contrast to the previous experiments, where tagged photon beams were used and only the scattered photons were registered, in the method proposed here and sketched in Fig. 2, non-tagged bremsstrahlung photons produced by an electron beam are used, and not only the angle and energy of the scattered photons but also the angle and energy of the recoiling protons (deuterons/helium ions) are measured. This is achieved with the hydrogen/deuterium/helium ionization chamber (IC), which acts as target as well as detector [19,20].

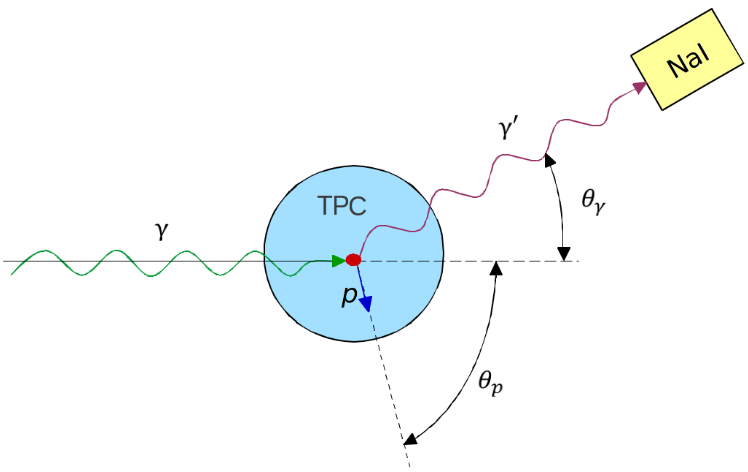

Fig. 2. Experimental method (schematic). A photon beam with a full bremsstrahlung spectrum is scattered from a gaseous hydrogen/deuterium/helium target inside a high pressure ionization chamber (TPC), the energy of the scattered photons is determined in a γ-detector under a certain angle. By detecting the scattered bremsstrahlung photon in coincidence with the recoiling proton (deuteron) in the ionization chamber the incoming photon energy is determined.

The whole experimental setup consists of a bremsstrahlung photon facility, a specially designed high pressure hydrogen (deuterium, helium) ionization chamber which serves as target and detector of the recoil proton (deuteron, helium isotopes), and two NaI gamma spectrometers (see Fig. 3).

In general, the proposed experimental method increases the luminosity and lowers the background considerably, especially below 50 MeV. In total, expected yields from an experiment based on the technique described here are at least an order of magnitude larger than those in the best recent γ-d Compton scattering experiments [16] and are compatible with the one for the proton recently performed by the A2 Collaboration [2-4].

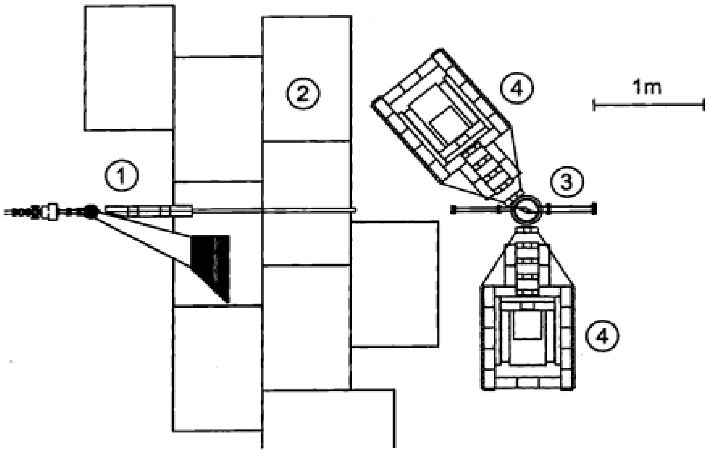

Fig. 3. General view of the experimental setup: 1 - bremsstrahlung facility, 2 - concrete shielding, 3 - high pressure ionization chamber, 4 - γ- spectrometers.

3.2. Bremsstrahlung photon facility

In Fig. 4, a schematic view of the high-energy bremsstrahlung photon facility built at the S-DALINAC [21] is shown as an example. This setup generates a high-intensity, nearly background-free photon beam. For optimal focusing and position corrections of the electron beam impinging on the radiation target, a triplet of quadrupole lenses and two pairs of vertical and horizontal correction magnets are used. To control the electron beam position, different diagnostic tools are installed (see Fig. 4). The fully controlled electron beam is transformed into a photon beam by passing through a 0.3 mm (corresponding to 0.1 radiation length) thick bremsstrahlung-radiator made of gold. Directly behind the radiator, the electrons are deflected out of the forward direction into a beam dump by means of a dipole magnet. This beam dump was specially constructed at S-DALINAC to stop most of the electrons without creating considerable background from bremsstrahlung photons and neutrons. It consists of three radiation lengths of aluminum plates and additional 200 mm of lead, both placed electrically insulated within a concrete wall. This electron beam dump is also used as a Faraday cup for measurement of the electron beam current. Behind the cleaning magnet the photon beam is collimated first in a three-stage lead collimator, consisting of several layers with different slit size parameters, and some additional layers of polyethylene as shielding against neutrons produced in the collimator. After the passage through a ~ 3 m concrete wall and a second lead collimation system the photon beam enters the experimental hall, where the Compton scattering set-up (Fig. 3) is installed.

In order to determine the cross sections for the Compton scattering off the proton (deuteron, helium) with the reported technique, it is essential to know the shape of the energy spectrum of the beam. The shape of this spectrum is extracted with the above-mentioned γ -spectrometer. Figure 5 shows the energy spectrum of the bremsstrahlung beam measured with the above-mentioned γ-spectrometer in comparison with the results of GEANT4 calculations. Excellent agreement is observed. With a knowledge of the response functions of the NaI(Tl) crystals it is possible to evaluate the shape of the energy spectrum of the incoming bremsstrahlung beam.

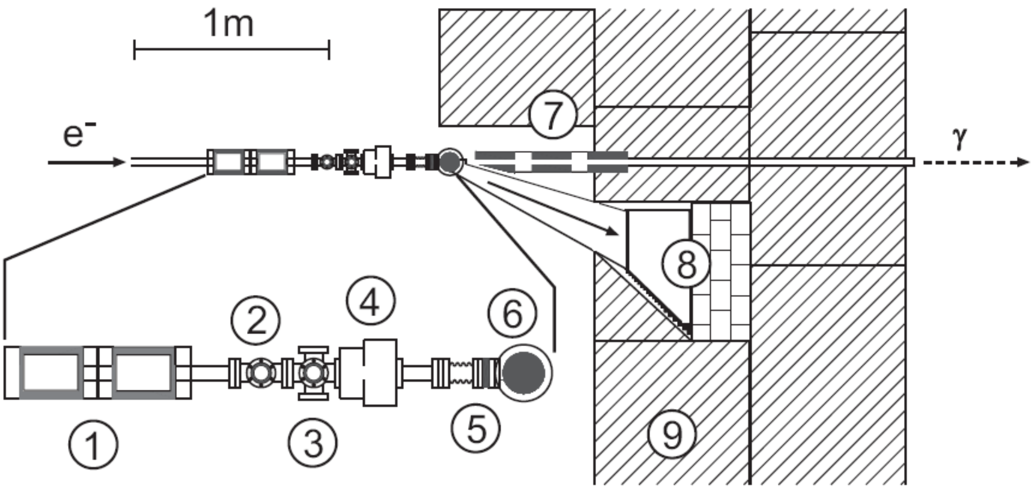

Fig. 4. Set-up of the bremsstrahlung facility: The electron beam from the S-DALINAC passes (1) – dipole magnets for electron beam corrections, (2) - a wire scanner for beam diagnostics, (3)- beam position targets, (4) - a beam intensity and position rf monitor, (5) - a bremsstrahlung converter target. (6) - A dipole cleaning magnet bends the electrons into an electron beam dump, (7) - a collimation system for produced γ beam, (8) - an electron beam dump (Faraday cup), (9) - concrete shielding.

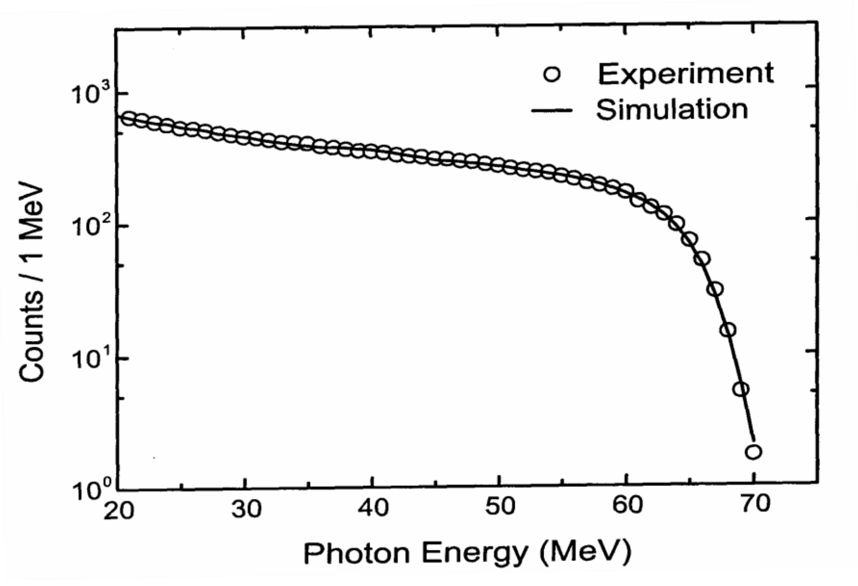

Fig. 5. Bremsstrahlung spectrum of the collimated bremsstrahlung approximately 3 m behind the bremsstrahlung target. Circles correspond to the measured bremsstrahlung spectrum taken at an electron energy E_0 = 71.3 MeV (electron beam current is 200 pA). The line shows a spectrum simulated with GEANT4.

3.3. Gamma ray spectrometers

In order to increase the statistics in the spectra requiring a coincidence between the recoiling particle and the scattered photons, two NaI(Tl) detectors are used simultaneously under the angles θ_γ (θ_γ = 90° and 130°). These γ-detectors used to detect the photons scattered from a protons (deuterons) are 10in ×14in in size (Fig. 6).

The NaI(Tl) photon spectrometers for detecting the scattered photons are items on loan from the Institut für Kernphysik of the Johannes Gutenberg-Universität Mainz. Compton scattered photons from the ionization chamber enter these γ-spectrometers through collimation systems, which determine a solid angle of about 25 msr. With this collimator system only the inner part of the γ detectors is hit, which reduces the low-energy tails in the response functions.

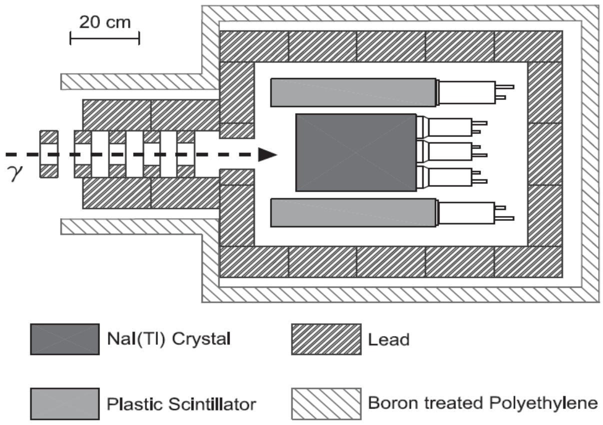

Fig. 6. Layout of the γ -spectrometer with a 10in × 14in NaI(Tl) crystal, active and passive shielding and the collimation system.

An energy calibration was achieved up to E_γ = 4.44 MeV with the help of standard γ-sources. At higher energies, the energy calibration was determined by using an electron beam with a known energy scattered from an aluminum target replacing the hydrogen ionization chamber. According to GEANT4 simulations, the response functions of the detectors for photons and electrons are practically identical. An extrapolation with the energy calibration parameters to the low-energy region shows good agreement with the results of the γ-source measurements (Fig. 7).

Since these detectors work as trigger detectors and the dead time of the ionization chamber is rather long (about 5µs), it is essential to minimize their background counting rate. Therefore, the NaI(Tl) crystals are well shielded (see Fig. 6). Plastic scintillators of 100 mm thickness act in anti-coincidence as active shielding against cosmic muons. Cosmic muons produce signals in NaI(Tl) crystals, with sizes almost evenly distributed in the energy interval of interest from 20 MeV to 100 MeV. Beam-related sources of background in the NaI(Tl) detectors are associated with the beam collimation system and the electron beam dump. To suppress these contributions, the scintillators are surrounded by 100 mm lead and by 50 mm of borated polyethylene, the latter acting against a possible neutron background, which may cause (n,γ) reactions in the NaI(Tl) detectors.

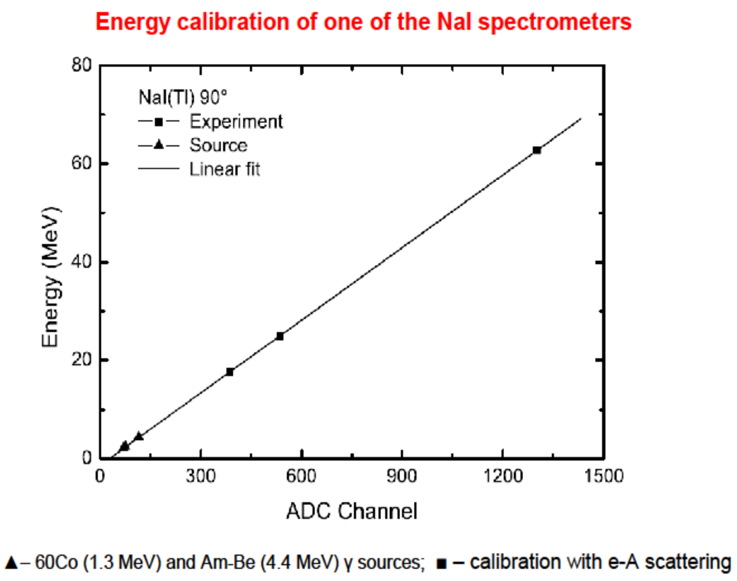

Fig.7. Energy calibration of the NaI(Tl) detector placed at 90° with elastic scattering electrons (squares) and radioactive gamma source (triangles).

3.4. High pressure ionization chamber

Several special high-pressure hydrogen-filled (H_2, D_2, $^{3,4}He$) ionization chambers (IC) were constructed and manufactured at the Petersburg Nuclear Physics Institute (PNPI) [20, 21]. It is essential that the IC provides practically 100% detection efficiency for the recoil particles (proton, deuteron or helium) in the chosen energy range ($E_{p,d}$ = 0.5 — 15 MeV). The ionization chamber has a cathode, a grid and two anode planes divided in strips. The body of the chamber is made of stainless steel with a wall thickness of 20 mm. The photon beam enters (leaves) the chambers through 6 mm beryllium windows. This material was chosen in order to minimize the absorption of photons and production of Compton electrons and $e^+ e^-$ pairs. The Compton scattered photons on hydrogen at the selected angles (θ_γ = 90° and 130°) leave the IC through 15 mm beryllium windows to the γ-spectrometers described above. The IC is operated in the electron collection mode, i.e. the signal results from the electrons collected after ionization produced by protons(deuterons). The applied high voltages are -60 kV on the cathode and -5 kV on the grid, the anode being at zero potential. The electron drift times are ~ 5 μs and 0.12 μs for the cathode-grid distance (26 mm) and grid-anode distance (1.3 mm), respectively.

To measure the energy and the angle of the recoil proton, a special geometry of the IC anode is used. It is designed to detect tracks of recoil protons in presence of background from tracks of Compton scattered electrons and secondary electron-positron pairs. To detect the small number of scattered protons in a regime of many Compton-scattered electrons, the two anodes of the IC are segmented into strips. These strips are oriented in the direction of the recoiling protons. One should notice that the direction of the scattered protons is defined mainly by the scattering angles of the photons, whereas the dependence of the proton recoil angles on the energy of the incident photons is negligible.

Figure 8 shows the geometry of the multi-strip anode plane of the IC for θ_γ = 130°. In particular, in the case of Compton scattering under θ_γ = 130°, the proton recoil angle is θ_p ~ 22°.

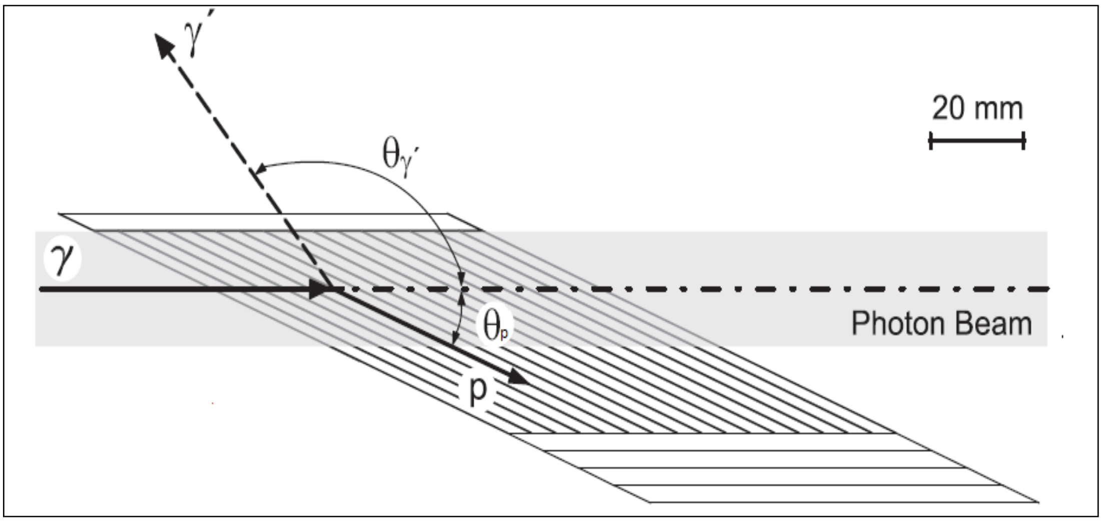

Fig. 8. Top view of a multi-strip anode plane: The 2 cm broad photon beam enters the volume of the IC from the left side. In case of a Compton scattering process under θ_γ = 130° angle the backscattered proton gets a momentum along an anode strip (θ_p = 22°).

For the case of Compton scattering under θ_γ = 90°, the proton recoil angle is θ_p ~ 44°. Along its path, the proton ionizes hydrogen molecules. The ionization electrons move towards the anode and are collected there on one or two anode strips. When Compton scattered electrons and electron-positron pairs are formed, they have angles different from the recoil protons. The charges released by them are collected by several strips and produce on them small signals. The energy resolution for recoil particles depends from electronic and beam noise. The electronic noise is about 20 keV and the noise from the beam is estimated from Monte Carlo simulations to be about 40 keV at maximal electron beam current 50 µA. The recoil particle polar angle resolution depends on the recoil particle range. For example, for particle range 50 mm, the angle resolution is estimated about 3 degrees. The correlations of the energy deposit (measured with high energy resolution) and polar angle of the recoil particle in the TPC allows efficient suppression of backgrounds (in combination with information on the scattered photon from the NaI crystals).

3.5. Test experiments

Test experiments were performed at the S-DALINAC using bremsstrahlung photon beams with endpoint energies E_γ of 60 MeV and 79.3 MeV [20]. Electron beam currents ranged from 1 to 3 µA. The IC was filled with hydrogen gas of high purity (level of the impurity less than 1 ppm) at a pressure of 75 bar. In these test experiments about 5000 Compton scattered events in total were collected in coincidence with recoil protons. The measured energy correlation between the scattered photons and recoiled protons ($E_{\gamma'}$, E_p) is shown in Fig. 9 for the data taken at E_γ = 60 MeV, θ_γ = 130°. The experimental data are in good agreement with the expected kinematical relation. This figure also demonstrates that the background is rather small. Events on the left side of the ($E_{\gamma'}$, E_p) correlation curve are partly due to the tails of the γ response function and partly due to background, which may be reduced in the future by building additional shielding for the γ spectrometers.

The results of two test runs have shown that future high-statistics experiments to determine α and β are feasible.

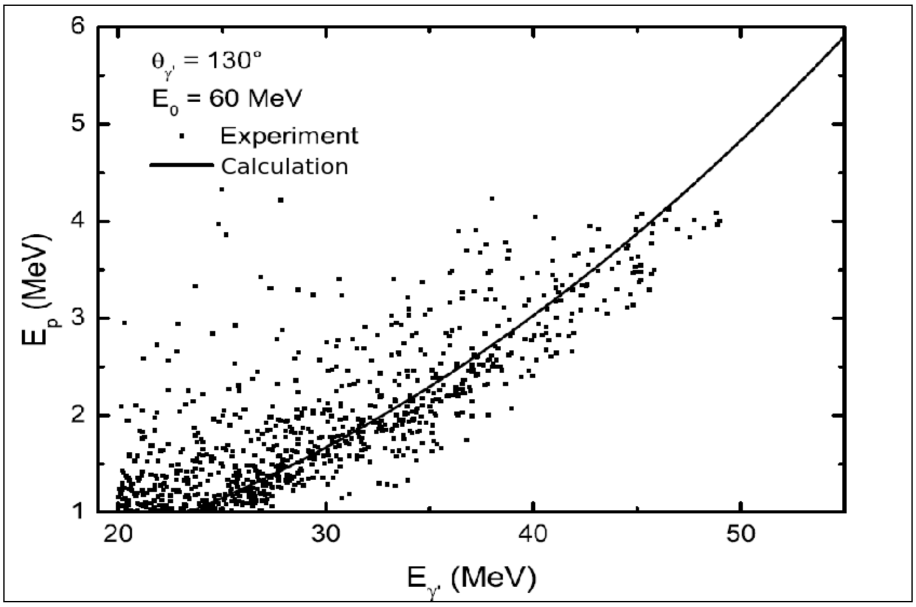

Fig. 9. Measured energy correlation of the scattered photons ($E_{\gamma'}$ > 20 MeV) and recoil protons (E_p > 1 MeV) in comparison with the expected kinematic relation for $E_{\gamma'}$ and E_p (solid curve) for the data taken at E_γ = 60 MeV and θ_γ =130°. The proton recoil energies are determined from the measured charges, collected on the IC anodes.

4. Required Precision

We propose to measure the energy dependence of the differential cross section $d\sigma(E_\gamma,\theta_\gamma)/d\Omega$ for Compton scattering of photons on protons, deuterons and helium ions in the energy range from 20 to 100 MeV at MESA (and up to the pion photoproduction threshold for experiments in combination with A2 setup at MAMI, see Sec. 6) simultaneously for two photon scattering angles (θ_γ = 90° and 130°). Our goal is to measure both α and β with total uncertainties (Δα and Δβ) less than 0.15×10^{-4} fm^{-3}. In order to achieve such level of precision, we plan to determine the individual differential cross section to a minimum of 0.5% statistical accuracy (the energy bin ~ 4 MeV) in the relative measurements. The preliminary estimations of the planned experiment show that we need to register about 4×10^6 of the Compton scattering events at each of the two angles (θ_γ = 90° and 130°).

4.1. Statistical uncertainties.

The statistical uncertainties were estimated by Monte Carlo simulations of differential cross section using low energy expansion. The energy range for Compton scattering photons was from 20 – 100 MeV.

The result of fitting (see Fig. 10) with four free parameters α, β, K_1, K_2 (where K_1 and K_2 are the normalization factors for two angles θ_γ = 90° and 130°) of a Monte-Carlo simulated differential cross sections $d\sigma(E_\gamma,\theta_\gamma)/d\Omega$ give us the following values for the statistical precision of Δα and Δβ (for total statistics of 8 million events):

$$\Delta\alpha = 0.07\times10^{-4}\ \text{fm}^{-3} \text{ and } \Delta\beta = 0.11\times10^{-4}\ \text{fm}^{-3}.$$

The normalization factors depend on the photon beam intensity, the target thickness, the solid angles, the efficiencies of the γ and recoil particles detectors.

It is important to note that the normalization factors can be determined simultaneously with values of polarizabilities and such way most part of systematical errors are cancelled. The cross sections for coherent scattering on the deuteron case are very close to the ones for the proton. The main kinematical difference is that the recoil deuteron energy is about twice smaller compared to the proton energy (for the same energy and angle of scattered photons). The background for the deuteron of course is higher due to quasi-elastic scattering on the proton inside deuteron. However, our experimental method (TPC as an active target) allows to use the correlation between the energy of the recoil particles (proton or deuteron) and energy of photons to suppress such backgrounds. Still, detailed Monte Carlo simulations need to be performed to study these aspects.

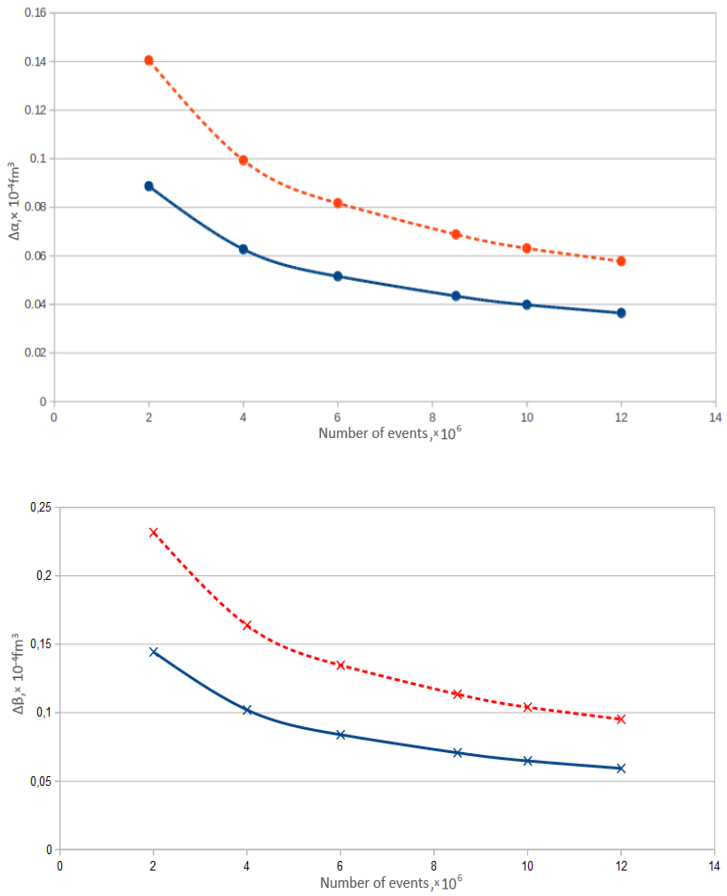

Fig. 10. Statistical uncertainties Δα and Δβ in function of the number of total detected scattering events at the two angles θ_γ = 90° and 130°. The calculation were performed with two free parameters (α ,β) — blue curve and with four free parameters (α, β, K_1, K_2) — red curve, where K_1 and K_2 are the normalization factors for each two angles θ_γ = 90° and 130°, respectively.

5. Counting rate

An estimate of the count rate is discussed below. Average values are used and are intended to represent (roughly) the count rate in the detectors. The count rate ($Y_{\gamma p}$) of the coincident detection of the scattered photon in the γ-detector with the recoil particle in the ionization chamber for the photon energy E_γ and the scattered photon polar angle θ_γ is given by:

$$Y_{\gamma p}(E_\gamma,\theta_\gamma) = d\sigma(E_\gamma,\theta_\gamma)/d\Omega \cdot N_\gamma(E_\gamma) \cdot t \cdot \Delta E_\gamma \cdot \Delta\Omega \cdot \varepsilon_{det} ,$$

where $d\sigma(E_\gamma,\theta_\gamma)/d\Omega$ is the differential cross section for Compton scattering at the photon angle $\theta_\gamma$and the photon energy E_γ, $N_\gamma(E_\gamma)$ is the photon beam intensity, t is the target thickness, ΔE_γ is the energy bin, $\Delta\Omega$ is the solid angle of the bin and ε_{det} is the detection efficiency for the scattered photon. The efficiency of the detection of the recoil proton is close to 100% (in the recoil energy range 0.5 – 15 MeV) and will be controlled during the experiment with a special pulse generator.

As an example, let us estimate expected count rates at E_γ = 60 MeV. These rates depend mainly on three experimental parameters, viz. the photon flux, the target thickness and the solid angle of the γ spectrometers. The corresponding information is taken from the test experiment at S-DALINAC [20]. To calculate the count rate, we make the following assignments for the various parameters:

1) differential cross section, $d\sigma(E_\gamma,\theta_\gamma)/d\Omega$ ~12nb/sr (rough average for E_γ from 20 to 100 MeV and θ_γ = 90° and 130°).
2) photon beam intensity, $N_\gamma(E_\gamma) = 2\cdot10^9$ MeV^{-1} s^{-1}, at E_γ = 60 MeV and $N_\gamma = 2\cdot10^{11}$ s^{-1} in the photon energy range of 20 – 100 MeV (taken to be a S-DALINAC test experiment value assuming an electron energy of 110 MeV at a beam current of 50 μA).
3) target thickness $t = 4\cdot10^{22}$ cm^{-2}, at p = 75 bar of the gas (H_2) pressure and for x =10 cm (linear thickness of the gas).
4) solid angle, $\Delta\Omega$ = 25 msr, for NaI entrance collimator diameter of 12 cm and NaI distance from the front face to the IC target of 70 cm.
5) ΔE_γ = 4 MeV is the energy bin and ε_{det} ~ 1 for NaI detector.

Using these values in the above expression for the count rate, we obtain a rate of ~ 400 counts/hour at E_γ = 60 MeV and ΔE_γ = 4 MeV.

The differential cross sections $d\sigma(E_\gamma,,\theta_\gamma)/d\Omega$ in the energy range of ~20–100 MeV for two scattering angle settings (θ_γ = 90° and 130°) can be measured with a statistical uncertainty better than 0.5% in each energy bin (ΔE_γ = 4 MeV), the number of data points being ~20. To reach this statistical uncertainty, about $4\cdot10^6$ of Compton scattering events should be collected at each proposed scattering angle. This would require about 500 hours the beam time for hydrogen and deuterium used in the active TPC. The detailed systematic studies are underway and will be included in a full proposal for hydrogen, deuterium, and helium (to be submitted to PAC in the future).

6. Summary and outlook

The goal of this proposal is to measure the scalar electric and magnetic polarizabilities of the proton and neutron at the MESA accelerator with a high precision using a new method with detection of recoil fragments in the TPC. We propose to measure the energy dependence of the differential cross section $d\sigma(E_\gamma,\theta_\gamma)/d\Omega$ for Compton scattering of photons on protons or deuterons using a bremsstrahlung photon beam with the maximum photon energy of ~110 MeV. A peculiarity of the proposed experiment is that a bremsstrahlung photon beam is used and the recoil proton (deuteron) is detected with a high-pressure hydrogen-filled (H_2, D_2) ionization chamber which serves as an active target. A photon scattered within the gas volume of the chamber is registered by large NaI detectors in coincidence with the recoil particle.

The virtues of this method are as follows:

a) The measurements can be performed at a rather low photon energy allowing for the data analysis to be performed in a model-independent way. The experimental data can be normalized to the theoretical value of $d\sigma(E_\gamma, \theta_\gamma)/d\Omega$ at the primary photon energy ω of 20–30 MeV where the contribution from the polarizability terms is small.

b) The method provides effective background rejection due to strong correlation between the kinematic variables of the scattered photon and the recoil proton (or recoil deuteron) in the case of elastic scattering.

c) As there is no necessity to measure the primary photon energy in this case and the detection efficiency of the recoil particles is high (~100%), the count rate of Compton scattering in the proposed experiment is expected to surpass the tagged photon variant.

All this allows to hope that the coincidence method will provide the polarizability measurement results with a high precision. The method of the proposed experiment was previously tested at the electron accelerator S-DALINAC (Institut für Kernphysik, Technische Universität Darmstadt). The results of the test experiments are very promising showing that further high-statistics measurements are feasible [20].

The MESA accelerator, which is under construction now in Mainz, would perfectly meet the requirements of the proposed experiment. In order to collect the necessary number of Compton scattering events, a ~110 MeV electron beam is needed with an intensity of ~50 µA. A not tagged secondary bremsstrahlung photon beam produced by interaction of the electron beam with an Au target of 0.3 mm thickness (0.1 radiation lengths) will provide a counting rate about 10^4 events per hour. The differential cross sections $d\sigma(E_\gamma,\theta_\gamma)/d\Omega$ in the energy range of ~20–100 MeV for two scattering angle settings (θ_γ = 90° and 130°) can be measured with a statistical uncertainty better than 0.5% in each energy bin (of ~ 4 MeV), the number of data points being ~20. To reach this statistical uncertainty, about $4\cdot10^6$ of Compton scattering events should be collected at each proposed scattering angle. This would require about 500 hours of beam time. The statistical precision of the electric and magnetic polarizabilities extracted from thus obtained data sample is estimated to be $\Delta\alpha = 0.07\times10^{-4}$ fm^{-3} and $\Delta\beta = 0.11\times10^{-4}$ fm^{-3}, respectively. In order to determine the energy dependence of the cross sections for photon-proton (deuteron, helium) scattering, one should know the energy shape of the photon beam and the response functions of the NaI detectors, which could be measured in dedicated experiments. Such measurements should be performed with a precision better than 0.5%. The polarizabilities α and β are extracted by fitting the energy dependence of the differential cross section data for the chosen Compton scattering angles.

The main part of systematic uncertainties (absolute values of the photon flux, target thickness, values of solid angles and absolute efficiencies for detection of photons and recoil particles) are cancelled due to we proposed method of measuring only relative cross sections. The normalization factors can be determined simultaneously with values of polarizabilities and in such a way need only relative values of the detector efficiency and the energy shape of the bremsstrahlung spectra need to be controlled.

To conclude, the proposed experiment aims at an essential improvement of the precision in polarizability measurements for the neutron and will provide high-precision data on the proton with a new experimental approach.

We are currently considering the technical possibilities of running experiments with bremsstrahlung photons at MESA. Also, the systematics of the proposed measurement is under investigation and we are planning to prepare a full proposal after finalizing this work. In parallel, we are exploring the options of measuring another very promising option of measuring the nucleon polarizabilties with a TPC used as an active target in combination with the Crystal Ball/TAPS setup. Such a setup would open a new route for experiments profiting from combination of the detection of low energy recoil particles in combination with nearly 4π acceptance of the Crystal Ball/TAPS system at MAMI.

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