COMPTON SCATTERING ON PROTONS BELOW PION THRESHOLD: MEASUREMENT OF ELECTRIC AND MAGNETIC POLARIZABILITIES OF PROTON (PROJECT)

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1. Introduction

The generalized (or Compton) constants of the proton electric ($\overline{\alpha}$) and magnetic ($\overline{\beta}$) polarizabilities are extracted in the process of γp elastic scattering by observing a deviation of the measured differential cross section $d\sigma(\omega,\theta)/d\Omega$ (ω is the energy of the incident photons, θ is the scattering angle) from its point-like value $[d\sigma(\omega,\theta)/d\Omega]_{\text{point}}$ which takes into account only the charge (e), mass (m_p), spin of the proton. The theoretical expression for $d\sigma(\omega,\theta)/d\Omega$ based on the low energy theorem (LET) for Compton scattering amplitude expanded to the second order over ω can be written as follows (see V.A.Petrun'kin, Fiz. Elem. Chastits At. Yadra **12**, 692 (1981); A.I.L'vov and V.A.Petrun'kin, Lebedev Institute Preprint No 258, Moscow (1988)):

$$\frac{d\sigma(\omega,\theta)}{d\Omega}=\frac{d\sigma(\omega,\theta)_{po\,\text{int}}}{d\Omega}-\rho+O(\omega^4) \qquad (1)$$

$$\rho=\frac{e2}{4\pi m_p}\left(\frac{\omega'}{\omega}\right)^2(\omega\omega')\left[\frac{\overline{\alpha}+\overline{\beta}}{2}(1+\cos\theta)^2+\frac{\overline{\alpha}-\overline{\beta}}{2}(1-\cos\theta)^2\right].$$

Here ρ is the structure term, ω' is the energy of scattered photon, $O(\omega^4)$ are the neglected terms of higher order structure constants. It is supposed that the terms $O(\omega^4)$ are small for $\omega << m_\pi$ (m_π is the pion mass). The sum ($\overline{\alpha}+\overline{\beta}$) is also constrained by the dispersion sum rule (see A.M.Baldwin, Nucl. Phys. **18**, 1612 (1960); A.M. Damashek and F.J.Gilman, Phys.Rev. **D1**, 1319 (1970)):

$$\overline{\alpha}+\overline{\beta}=\frac{1}{2\pi^2}\int_0^\infty\frac{d\omega}{\omega^2}\sigma_{\text{tot}}(\omega)=(14.2\pm0.3)\cdot10^{-4}\,\text{fm}^3,$$

where $\sigma_{tot}(\omega)$ is the total γp cross section. The integral is evaluated using the experimental data $\sigma_{tot}(\omega)$ for ω up to 30 GeV with a theoretical ansatz for higher ω (however, indicated errors are certainly too small).

The contribution of the structure term ρ to the LET formula (1) is illustrated in Fig. 1. The dotted lines are $[d\sigma(\omega,\theta)/d\Omega]_{\text{point}}$, the solid lines are $d\sigma(\omega,\theta)/d\Omega$ calculated for several values of $\overline{\alpha}$ from $\overline{\alpha}$ = 9.2 (upper curves) to $\overline{\alpha}$ = 17.2 (lower curves) with a step $\delta\overline{\alpha}$ = 1.6. The sum ($\overline{\alpha}+\overline{\beta}$) is fixed to be 14.2 (here and further $\overline{\alpha}$ and $\overline{\beta}$ are defined in units of $10^{-4}\,\text{fm}^3$).

Fig. 1 shows also the experimental data which have been obtained using the tagged photons method (University of Illinois at Urbana-Champaign, see F.J Federspiel *et. al.*, Phys.Rev. Lett. **67**, 1511 (1991); Saskatchewan Accelerator Laboratory, see B.E.Mac Gibbon *et. al.*, Phys.Rev. **C52,** 2097 (1995)).

The fit with LET- formula to the Urbana experimental data shown in Fig. 1 gives

$\overline{\alpha}=10.6\pm2.2\pm1.4$ $\overline{\beta}=3.6\pm2.2\pm1.4$ ($\overline{\alpha}+\overline{\beta}=14.2$ *fixed*),

$\overline{\alpha}=9.8\pm2.7\pm1.9$ $\overline{\beta}=2.5\pm3.2\pm2.4$ ($\overline{\alpha}+\overline{\beta}$ *is not fixed*).

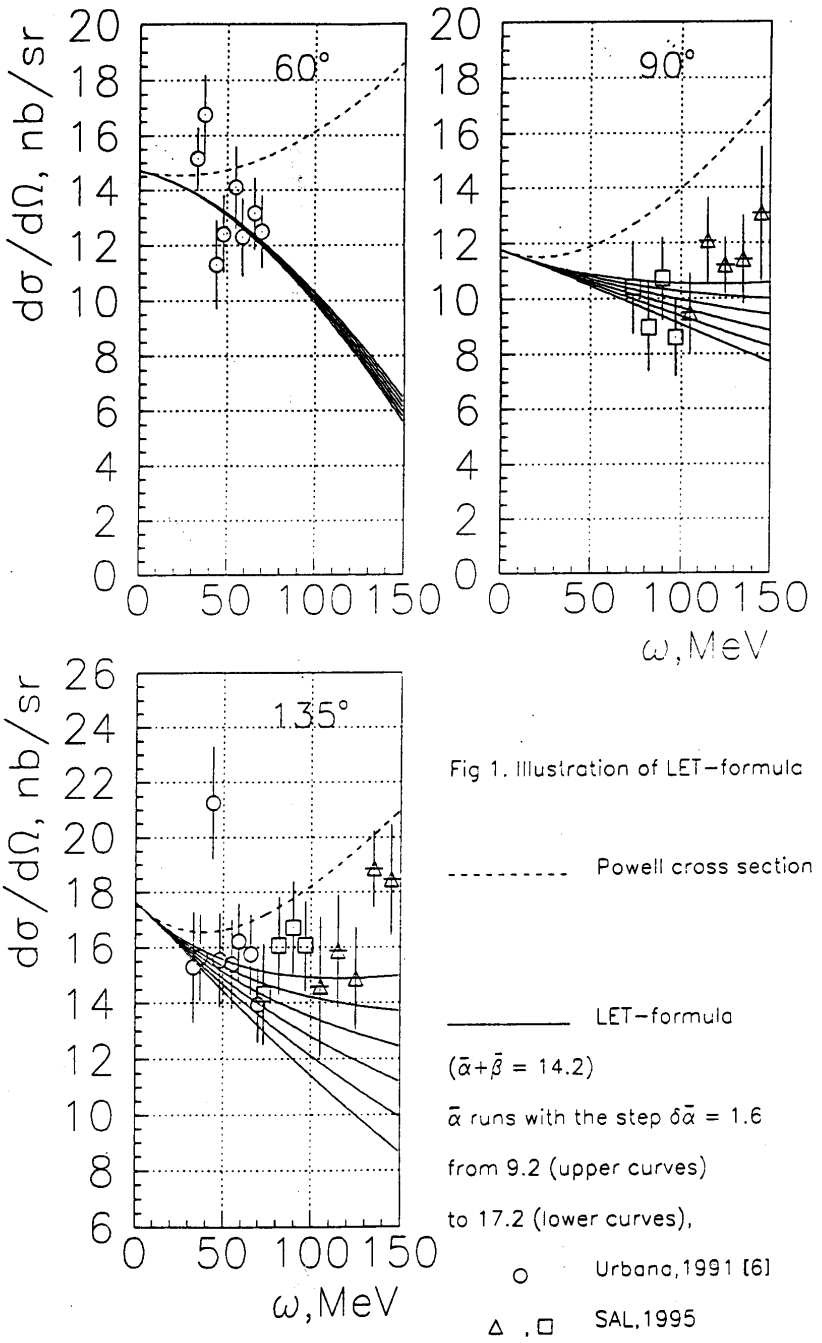

Fig. 1. Illustration of LET – formula

Here and further the first quoted error is statistical, the second is systematic. The fit with the formula got in the theoretical model-dependent approach (MDA), that aims to describe γp scattering up to photons energies comparable to the pion mass, to the SAL experimental data shown in Fig.1 gives

$\overline{\alpha} = 12.5 \pm 0.6 \pm 0.7 \pm 0.5$ $\overline{\beta} = 1.7 \pm 0.6 \pm 0.7 \mp 0.5$ ($\overline{\alpha} + \overline{\beta} = 14.2 \pm 0.5 is fixed$),

where the last errors are model-dependent. The some previous experiments, that have been attempted to determine the proton polarizabilities, are summarized, for example, in Refs. [1, 2].

An essential improvement of the data on the proton polarizability is important for the test of various nucleon models as well as for the extraction of the neutron polarizability from the data on elastic and inelastic scattering of photons by deuterons.

2. Experimental method

The aim of the proposed experiment is to determine a model-independent value of proton electric ($\overline{\alpha}$) and magnetic ($\overline{\beta}$) polarizabilities with a precision $\leq 0.5\%$. This aim could be reached by measurements of the energy dependence of the cross section for γp elastic scattering, $d\sigma(\omega,\theta)/d\Omega$, with a statistical accuracy better than 1% in the photon energy of 20–100 MeV for two values of the scattering angle θ (θ about 90° and 130° is assumed). These measurements are problematic within real beam time using a tagged photons method because of low intensity of the tagged photons beam ($\approx 10^{6}$ photons /MeV·sec). On the basis of the proposed method these measurements could be done using an untagged bremsstrahlung photon beam of $\approx$100 MeV energy and of a few μA current. The scattered photons with energy ω' ($\omega' \approx$ 20–100 MeV) will be detected by a large volume NaI γ-spectrometer with a solid angle for detection of 0.025 sr ($\Delta\theta \approx \pm 5^{\circ}$).

However measurements of the scattered photons with the γ-spectrometer alone are not enough for clean separation of the Compton scattering events from the background. For example, an important background reaction is the production of the electron-positron pairs in the electric field of the proton followed by a bremsstrahlung photon emitted by electrons (positrons) in the same field. The information about this effect is contained in Ref. [2] but the data mentioned in there should be divided by factor 2π, as the author of these calculations informed us. To avoid the background problems, we propose to detect the recoiled protons in coincidence with the scattered photons. We propose to use a special high pressure hydrogen-filled Ionization Chamber (IC) which serves as both a target and a recoiled proton detector. The recoils will be detected in the energy range $0.8 \leq E_p \leq 8$ MeV. (E_p-ω'')-correlations will be used to select clean Compton scattering events (ω'' is the amplitude of a γ-spectrometer signal expressed in energy units). Two possibilities have been considered for the extraction of the relative energy dependence of the values $d\sigma(\omega,\theta)/d\Omega$ with small enough systematic errors.

The first possibility is based on a supposition that the response function of the γ-spectrometer:

$$F(\omega'',\omega') \equiv \frac{dn(\omega'',\omega' = const)}{d\omega''}$$

will be determined experimentally in a separate measurement with a sufficient accuracy. Then the differential cross sections $d\sigma(\omega,\theta)/d\Omega$ averaged over the intervals $\Delta\omega''$ will be determined from integral equation:

$$[Y_{\gamma p}(i,\overline{\theta_\gamma})]_{\omega_i''}^{\omega_{i+1}''} = K_1 \int_{\omega_i}^{\omega_{\max}} \frac{dN(\omega,\omega_{\max})}{d\omega} \frac{d\sigma(\omega,\overline{\theta_\gamma})}{d\Omega} P(i,\omega')d\omega ,$$

where $Y_{\gamma p}(i,\overline{\theta_\gamma})$ is the measured yield of the γp-scattering events in intervals $\Delta\omega''$, K_1 the is normalization factor that takes into account the target thickness, the solid angle of the γ–detector, the efficiency of the IC for detection of the recoiled protons; $\frac{dN(\omega,\omega_{\max})}{d\omega}$ is the spectrum of the incident photons; $P(i,\omega') = \int_{\omega_i''}^{\omega_{i+1}''} \frac{dn(\omega'',\omega')}{d\omega''} d\omega''$ is the probability of registration of the scattered photons with

energy ω' in the amplitude interval $\Delta\omega_i''$. The shape of the incident photon spectrum $\frac{dN(\omega,\omega_{\max})}{d\omega}$ will be determined with the same NaI spectrometer by detecting the incident photons

The second possibility is based on results of additional measurements of γe scattering permitting to avoid measurements of the response function of the γ-spectrometer and the shape of the incident spectrum $\frac{dN(\omega,\omega_{\max})}{d\omega}$. The scattering angle $\overline{\theta_{\gamma e}}$ will be fixed by the condition:

$$\omega_{\gamma e} = \omega_{\gamma p}\ ;\ \omega'_{\gamma e} = \omega'_{\gamma p}\ ;\ \frac{1}{m_p(1-\cos\overline{\theta_{\gamma p}})} = \frac{1}{m_e(1-\cos\overline{\theta_{\gamma e}})}\ .$$

In our case it makes $\overline{\theta_{\gamma e}} = 1.89°$ and $2.51°$ corresponding to $\overline{\theta_{\gamma p}} = 90°$ and $130°$. It is assumed that the peaks of the total absorption of the photon with energy ω_i' will be selected from two-dimensional distribution of the events $(E_p - \omega'')$. Then

$$[Y_{\gamma p}(i,\overline{\theta_{\gamma p}})]_{\omega_i'}^{\omega_{i+1}'} = K\int_{\omega_i}^{\omega_{i+1}'}\frac{dN(\omega,\omega_{\max})}{d\omega}\varepsilon(\omega')\frac{d\sigma(\omega,\overline{\theta})}{d\Omega}d\omega = K\frac{d\sigma(\omega_{0i},\overline{\theta})}{d\Omega}\int_{\omega_i}^{\omega_{i+1}}\frac{dN(\omega,\omega_{\max})}{d\omega}\varepsilon(\omega')d\omega\ ,$$

where $Y_{\gamma p}(i,\overline{\theta_{\gamma p}})$ is the yield of the scattered photons in the energy interval $\Delta\omega_i'$, $\varepsilon(\omega')$ is the photon detection efficiency, ω_{0i} is the average energy in the interval $\Delta\omega_i'$ and

$$\frac{d\sigma(\omega_{0i},\overline{\theta_{\gamma p}})}{d\Omega} = \frac{d\sigma(\omega_{01},\overline{\theta_{\gamma p}})}{d\Omega}\frac{Y_{\gamma p}(i,\overline{\theta_{\gamma p}})}{Y_{\gamma p}(1,\overline{\theta_{\gamma p}})}\frac{\int_{\omega_i}^{\omega_i'+\Delta\omega_i}\frac{dN(\omega,\omega_{max})}{d\omega}\varepsilon(\omega')d\omega}{\int_{\omega_1}^{\omega_1+\Delta\omega_1}\frac{dN(\omega,\omega_{max})}{d\omega}\varepsilon(\omega')d\omega}.$$

The ratio $\frac{\int_{\omega_i}^{\omega_i+\Delta\omega_i}\frac{dN(\omega,\omega_{\max})}{d\omega}\varepsilon(\omega')d\omega}{\int_{\omega_1}^{\omega_1+\Delta\omega_1}\frac{dN(\omega,\omega_{\max})}{d\omega}\varepsilon(\omega')d\omega} \equiv A_i$ is obtained by detection (with the same detector) of the photon scattered on free electrons, the scattered photon and the recoil electron being detected in coincidence. Then

$$\frac{Y_{\gamma e}(1,\overline{\theta_{\gamma e}})}{Y_{\gamma e}(i,\overline{\theta_{\gamma e}})} = \left[\frac{\sigma(\omega_{01},\overline{\theta}_{\gamma e})}{\sigma_i(\omega_{0i},\overline{\theta_{\gamma e}})}\right]_{theory}\times A_i\ ,\quad \text{where}\ \left[\frac{\sigma(\omega_{01},\overline{\theta}_{\gamma e}}{\sigma_i(\omega_{0i},\overline{\theta_{\gamma e}})}\right]_{theory_i}\ \text{is the calculated Compton differential cross section ratio.}$$

Thus the values $\frac{d\sigma_1(\omega_{0i},\overline{\theta_{\gamma p}})}{d\Omega}$ are determined from proportion:

$$\frac{d\sigma(\omega_{0i},\overline{\theta_{\gamma p}})}{d\Omega} = \frac{d\sigma\ (\omega_{01},\overline{\theta_{\gamma p}})}{d\Omega}\left[\frac{\sigma_1(\omega_{01},\overline{\theta}_{\gamma e})}{\sigma_i(\omega_{0i},\overline{\theta_{\gamma e}})}\right]_i\frac{Y_{\gamma e}(1,\overline{\theta_{\gamma e}})}{Y_{\gamma e}(i,\overline{\theta_{\gamma e}})}\frac{Y_{\gamma p}(i,\overline{\theta_{\gamma p}})}{Y_{\gamma p}(1,\overline{\theta_{\gamma p}})}$$

($\frac{d\sigma\ (\omega_{01},\overline{\theta_{\gamma p}})}{d\Omega}$ is the free parameter).

In order to have relative systematic errors of the values $\frac{d\sigma(\omega_{0i}, \overline{\theta_{\gamma p}})}{d\Omega}$ for the largest i (i max about 20–25 is assumed) less than 1% one should provide:

the accuracy of the energy scale of NaI-spectrometer at a level of 1–2%;

the accuracy of $\theta_{\gamma e}$ is $\pm 0.01°$ (on the base L = 10 m);

the difference between the effective IC volume for long and short tracks is estimated to be about 0.3%.

The plan view of the experimental layout is shown in Figs. 2, 3.

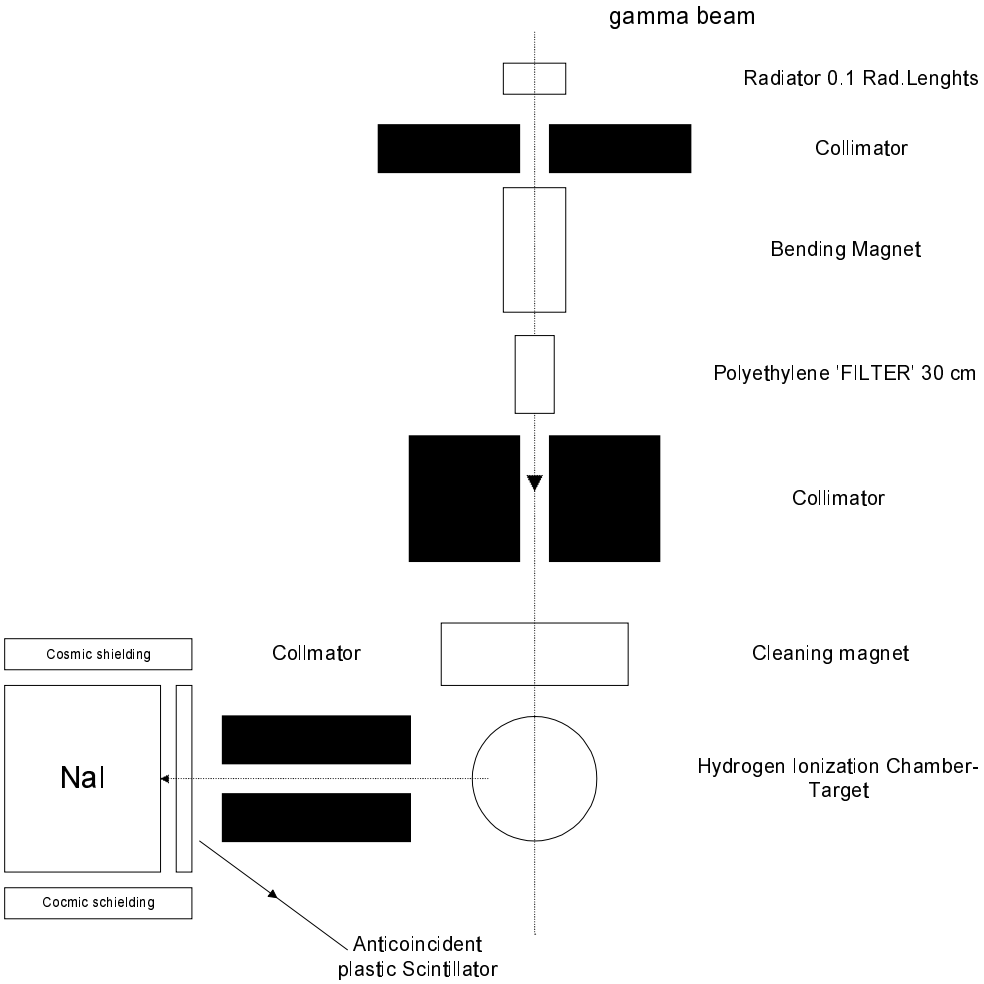

Fig. 2. Plan view of the experimental layout (γp scattering)

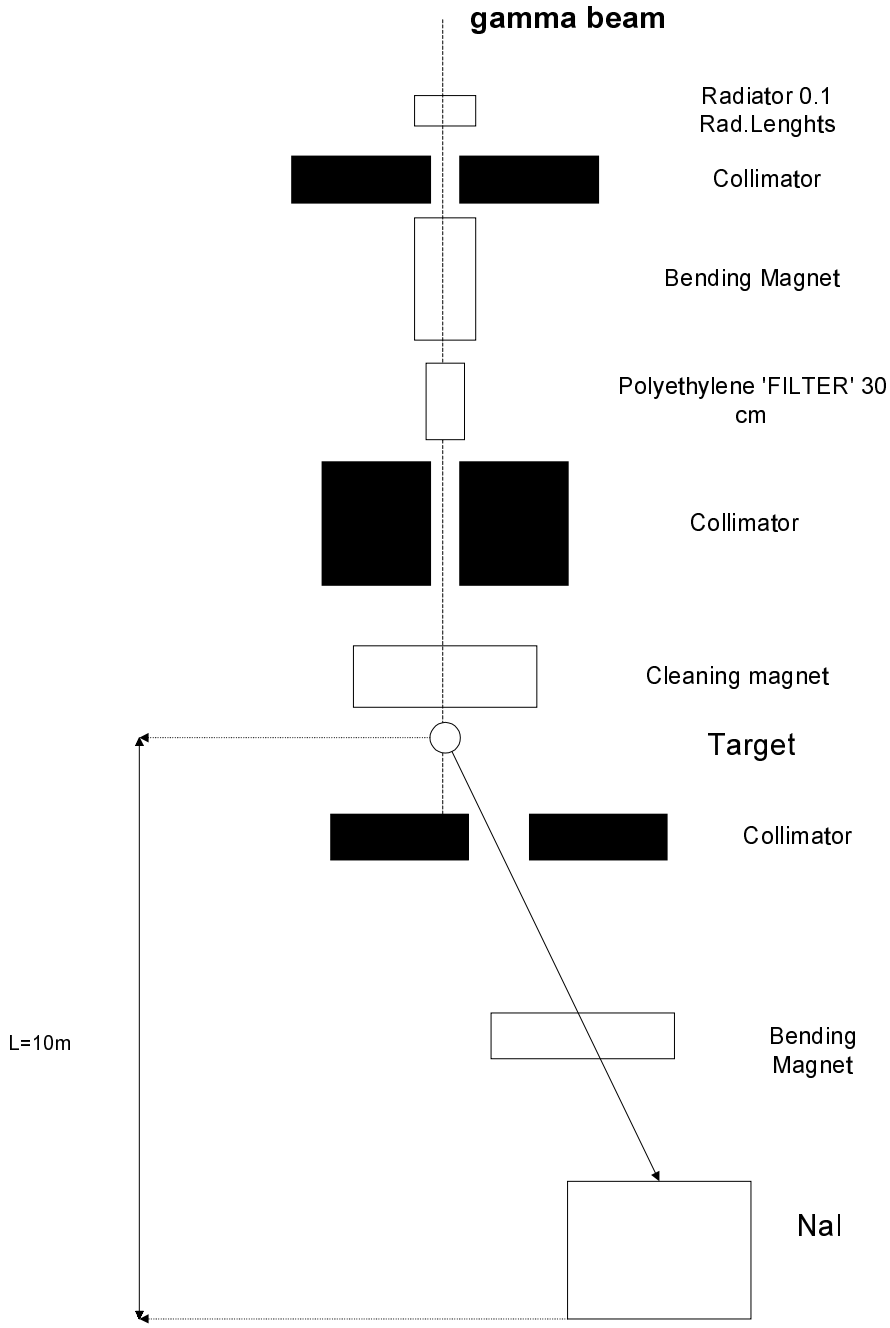

Fig. 3. Plan view of the experimental layout (γe scattering)

Fig. 4 shows the result of fitting by the LET-formula with four free parameters [$\overline{\alpha}$, $\overline{\beta}$, $b_1(\theta_1)$, $b_2(\theta_2)$] of the Monte-Carlo simulated experiment with the incident bremsstrahlung ($E\gamma_{max}$ = 130 MeV) beam scattered to $\theta_1 = 60°$ and $\theta_2 = 135°$ [2].

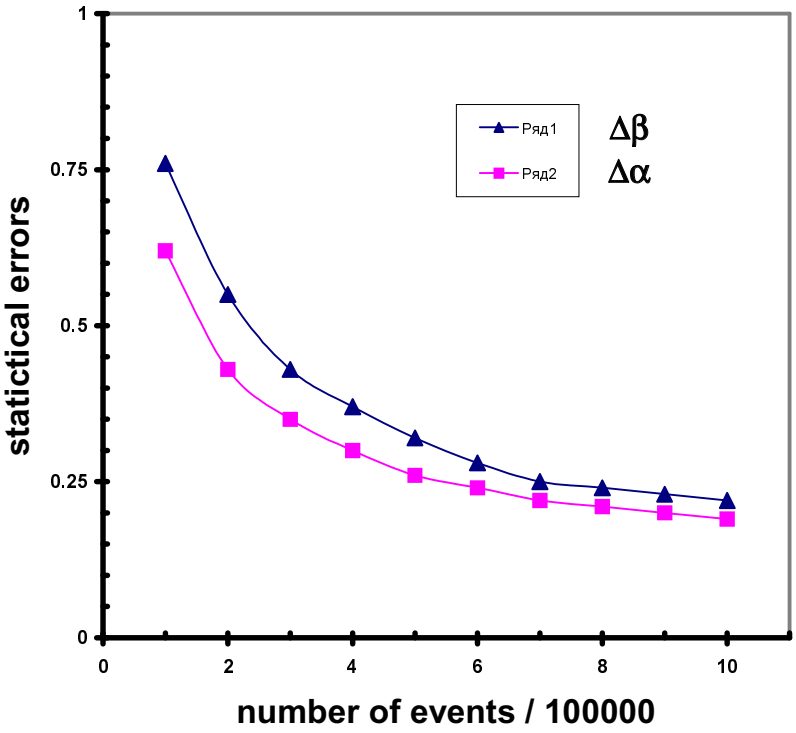

Fig. 4. Statistical errors in function of the number of detected scattering events

Here $\Delta\overline{\alpha}$ and $\Delta\overline{\beta}$ are the statistical errors of the parameters $\overline{\alpha}$ and $\overline{\beta}$ depending on the number of simulated scattering events for each angle.

3. Ionization chamber-target-detector of recoiled proton

The hydrogen high pressure ionization chamber (100 bars, ≈ 3×10^{22} protons/cm^2) consists of about 20 anodes in the form of strips (2.5 mm width each) in order to diminish the background produced by Compton recoiled electrons and e^+e^- pairs. The strips are oriented along the average recoil protons tracks direction. The projection of the track on the anode plane lies within one or two strips. The scheme of the anode block and some characteristics of valid anode signals are shown in Fig. 5.

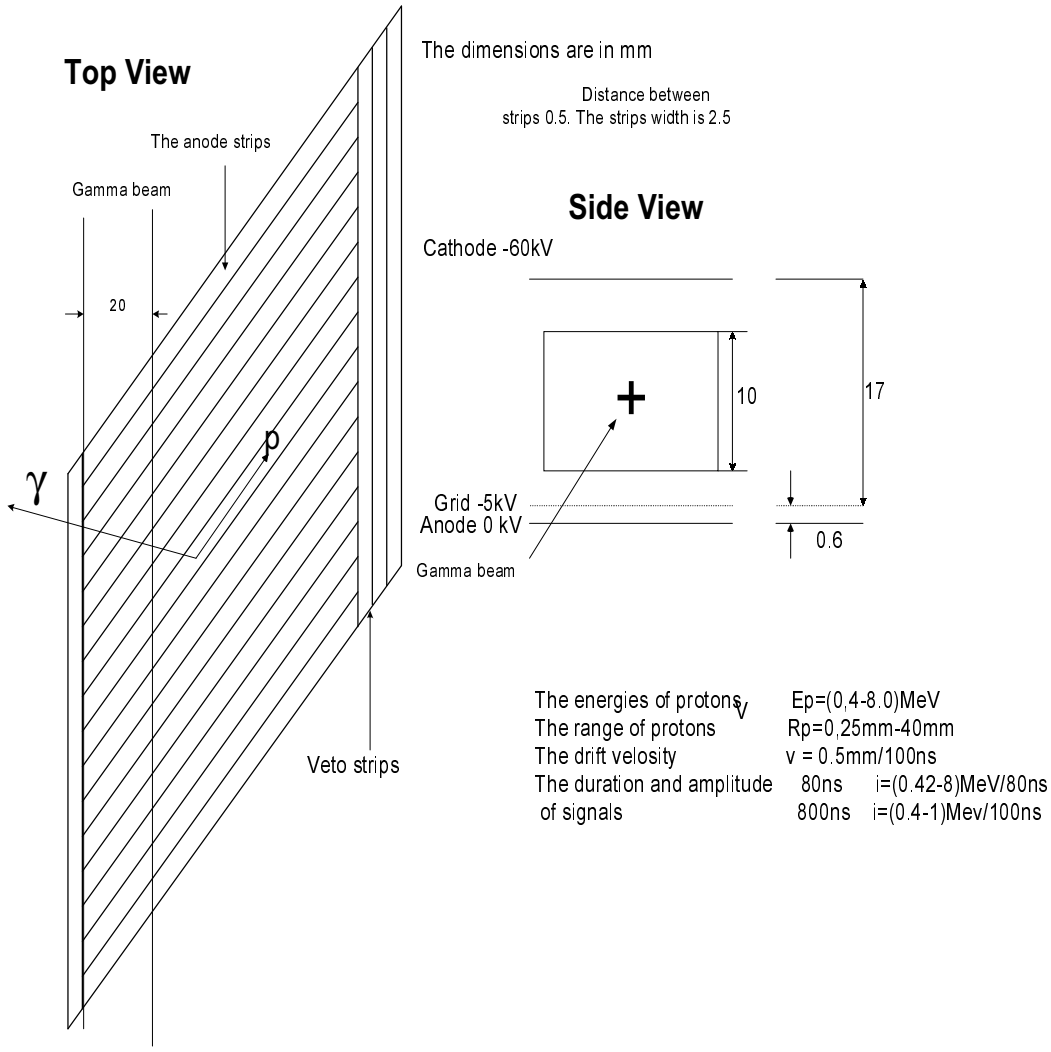

Fig. 5. Principal scheme of the Ionization Chamber electrodes
P = 100 bar, E = 32 keV/cm

The GEANT routine has been used for the background simulations. The background was calculated for the intensity of the incident bremsstrahlung beam with the energy

$$W = \int_0^{130MeV} \frac{dN(\omega)}{d\omega}\omega d\omega \approx 4x10^{12}\, MeV/s \quad [(\tfrac{dN(\omega)}{d\omega})d\omega = Wd\omega/\omega E_0].$$

The background anode current is shown in Table:

Table

The average background current at the IC in units of keV/100 ns.
In brackets are the numbers of events during 100 ns
(thickness of H_2 between the IC and the end of the cleaning magnet is about 15 cm).
a – ionization due to photon scattering inside the IC.
b – ionization by the particles produced upstream of IC.
a + b – sum current (average and fluctuations)

N	$\theta_p = 60^\circ$			$\theta_p = 20^\circ$		
	a	b	a+b	a	B	a+b
1	14.5(2.2)	121.7(20.1)	136 ± 28	38.8(4.2)	183.2(18.5)	223 ± 47
2	16.5(2.8)	119.0(20.0)	135 ± 28	38.8(4.2)	183.2(18.5)	229 ± 53
3	21.8(3.7)	119.0(19.0)	141 ± 30	62.0(5.3)	176.2(14.1)	238 ± 54
4	27.4(4.4)	116.0(18.8)	143 ± 30	82.0(6.9)	172.4(13.5)	254 ± 52
5	29.9(5.2)	112.0(18.3)	142 ± 29	106.2(8.5)	167.5(13.0)	274 ± 59
6	36.4(6.1)	109.0(18.0)	145 ± 30	116.0(9.8)	165.0(12.5)	281 ± 58
7	41.5(7.3)	106.0(17.5)	148 ± 30	135.0(11.0)	160.9(12.1)	296 ± 62
8	45.1(7.3)	104.0(16.3)	149 ± 31	147.0(12.0)	156.0(11.6)	303 ± 62
9	49.8(8.0)	103.0(16.8)	153 ± 31	157.0(13.2)	152.0(11.4)	309 ± 62
10	55.7(8.6)	101.0(16.5)	157 ± 31	177.5(17.8)	144.4(13.9)	327 ± 58
11	56.7(9.4)	100.0(16.3)	157 ± 31	188.0(15.6)	145.5(10.8)	334 ± 65
12	58.7(10.1)	99.0(16.0)	158 ± 31			
13	62,5(10.6)	99/0(16.0)	163 ± 32			
14	66.1(11.1)	100.0(15.8)	166 ± 32			
15	70.0(11.5)	96.5(15.5)	167 ± 32			
16	69.2(11.6)	94.0(15.2)	163 ± 32			
17	72.5(12.1)	92.6(14.9)	165 ± 32			
18	79.6(12.1)	92.6(14.9)	171 ± 32			
19	80.8(12.7)	90.0(14.4)	171 ± 32			

At such intensity of the photon beam about 10^6 useful events will be obtained after 400–500 hours of the beam time.

In addition we would like to notice that the proposed experimental method would be suitable for study of the elastic and inelastic photon scattering on deuteron to obtain the electric and magnetic neutron polarizabilities with high accuracy.

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