PART 1

QUANTUM ELECTRODYNAMICS

RECENT AND FUTURE HIGH ENERGY EXPERIMENTS ON QED NONLINEAR EFFECTS

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A short review of the experiments on photon elastic scattering and splitting on Coulomb field of nuclei as well as on multiphoton Compton scattering and Breit-Wheeler pair production in strong electromagnetic field is given. Possible new QED nonlinear experiments are discussed.

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1. INTRODUCTION

QED processes are listed in Table 1 together with key references of theoretical and experimental works. For the first time the high energy process of scattering when the energies of the colliding photons in cms is larger than the electron mass has been studied in the first publication of A.I. Akhiezer [2]. As it is seen from his monographs and his last talks A.I. Akhiezer kept his first love to this and other QED nonlinear processes during all his life. That is why it has been found reasonable to include this very short review talk on the status of experiments in the program of this conference.

The processes (1), (2) and (4) are theoretically studied for n = 1 (nω ≡ γ) only, while (7) for n >1 is only estimated. The study of many of these processes has begun after the invention of intense laser photon beams photon producing very strong electromagnetic fields. The field is strong if it is greater than the QED critical field

$$F_0 = \frac{m^2c^3}{e\hbar} = 1.3\cdot10^{16}\,\frac{V}{cm} = 4.4\cdot10^{13}\,Gauss\,.$$

Two invariants characterize the rate of these processes:

$$\eta = \frac{e\hbar F}{mc\omega} = \left(\frac{2n_\omega r_e^2\lambda}{\alpha}\right)^{1/2}$$

and

$$\Upsilon = \frac{\varepsilon\left(or\,\varepsilon_\gamma\right)}{mc^2}\,\frac{F}{F_0}\,.$$

In this expressions F is rms electric (E) or magnetic (H) field, ω, λ and n_ω are the photon frequency, wavelength and density, r_e is the electron classical radius, α = 1/137, ε and ε_γ are the electron and gamma quanta energy. Using laser intensity I in W/cm^2 one can write

$\eta = 7.5.10^{-10}\, I^{1/2}(W/cm^2)/\hbar\omega(eV)$,

$E(V/cm) = 19.4\, I^{1/2}(W/cm^2)$,

$n_\omega(cm^{-3}) = 2.10^8\, I(W/cm^2)/ђ\omega(eV)$.

The nonlinear effects are essential when the values of these invariants are of the order or greater than 1. For instance, if ђω = 1.17 eV, I = 0.5.10^{18} W/cm^2, ε = 50 GeV then η = 0.4, Υ=0.25.

Table 1. *High energy QED nonlinear effects*

№	Process	Reaction	Theory	Experiment
1	Light scattering by light	(nω)γ→γγ	[1-4]	Not observed [5-8]
2	Delbruck scattering	(nω)Z→Zγ	[4,9-11]	[12,13]
3	Photon splitting	γ Z→Zγγ	[4,14,15]	[16]
4	Coalescence of photons	(nω)γZ→Zγ	[4]	Not observed
5	Multiphoton Compton scattering	(nω)e→eγ	[17-20]	[21-22]
6	Multiphoton Breit-Wheeler	(nω)γ→ee	[18-20]	[22,23]
7	Multiphoton trident	(nω)e→eee	[22]	Not observed
8	Photon splitting in EM Field	γF→Fγγ	[24-26]	Not observed
9	Unruh effect (radiation)	eF→Feγ	[27-29]	Not observed
10	Field induced n processes (Cherenkov)	eF→Feω	[30-31]	Not observed

As it is seen from Table 1 only the elastic scattering (2) and splitting (3) of photons on nuclei as well as the radiation (5) and pair production (6) in strong field has been studied experimentally. The elastic scattering of photons on photons (1) is observed only with the help of virtual photons in e^+e^- collisions and it is not observed with real photons. There is a hope that the processes (7), (9) and (10) can be observed if the achieved laser intensities will be increased by one order. The processes (3) and (8) can proceed only in cosmological objects and no in terrestrial experiments in the near future. We do not include the W-boson photoproduction $\gamma e \rightarrow W\nu$ [32] and pair production in laser beam collisions $(n\omega)+(m\omega) \rightarrow e^+ e^-$ [33] processes into the Table 1, because they are rather elementary particle and low energy problems. We shall not also consider such development of the theory as the peculiarities of the nonlinear QED processes in single crystals [34,35] as well as some polarization effects in (1) and (6) [36] which increase the corresponding cross sections.

2. NOVOSIBIRSK EXPERIMENTS ON DELBRUCK SCATTERING (DS) AND PHOTON SPLITTING (PS)

In the work [13] results have been obtained for elastic scattering of photons with ε_γ = (1-7.3) GeV on nuclei Cu, Ag, Au and U under angles θ = (1-3) mrad in good agreement with the theory [10] taking into account the Coulomb corrections. The authors [13] also declared that as by product they have made the first observation of the splitting of photons (3) at the same energies. However, as it has been shown in [37] in the experiment [13] the process $\gamma Z \rightarrow e^+ e^- \gamma$ and not photon splitting was observed.

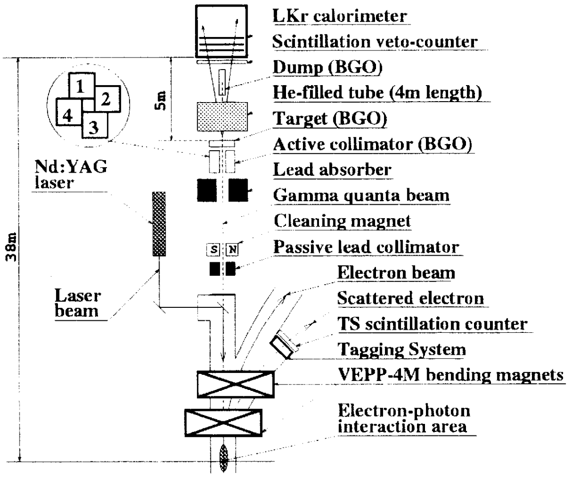

Fig. 1. The experimental arrangement of the Novosibirsk DS and PS experiments

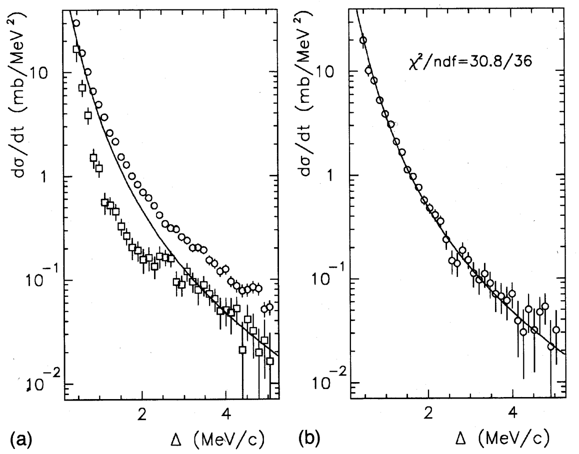

Fig. 2. dσ/dt vs momentum transfer Δ for BGO without a) and after b) subtraction of the background. The solid curve is the theory

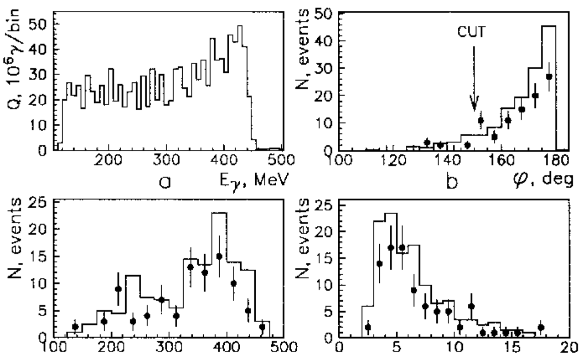

Fig. 3. The distributions a) of the tagged photon energy, b) over the complanarity angle, c) of the energy of the coplanar events and d) of the PS angles. The points and histogram are the experimental and Monte Carlo results

Recently, using the tagged Compton backscattered photon beam at VEPP-4M and a liquid krypton (LKr) calorimeter, new experimental study of (2) and first observation of (3) have been made by a BINP group [13] and [16], respectively. The experimental arrangement shown in Fig. 1 had the following main parameters: The tagged photons had energy ω = (120-450) MeV, $\Delta\omega/\omega \approx 0.013$; the thickness of the active collimator, target and dump BGO were 13.3, 1 and 10 r.l.

The LKr calorimeter allowed to measure the energy of scattered or splitted photons with $\sigma \approx 2.4\%/[\varepsilon(\mathrm{GeV})]^{1/2}$ and space resolution equal to (1-2.3) mm.

Table 2. *The comparison between the experimental and Monte Carlo results for different photon energy intervals. The data in each column are normalized to 10^9 initial photons*

Photon energy interval	140-450MeV	140-250MeV	250-350 MeV	350-450 MeV
Initial photons	902.10^6	275.10^6	260.10^9	367.10^9
Experiment	13172±232	16810±353	13252±301	10383±229
Simulation	12810±181	16709±329	12535±283	10079±209
DS	9120±111	12346±171	8884±150	6867±119
Compton Scattering	1334±45	1624±85	1254±80	1173±66
Secondary photons	52±8	60±16	57±16	42±13
PS	495±62	954±133	324±65	270±51
Without interaction	435±88	434±90	519±108	376±78
From BGO collimator	1374±124	1290±246	1497±214	12351±147

The following event separation criteria were required to separate the rare events in the large background:

1) One particle in the tagging system, the energy deposition;

2) in BGO collimator < 0.35 MeV;

3)in BGO target < 0.15 MeV;

4) in anticoincidence counter <0.4 MeV, background;

5) in first layer of LKr > 80 MeV;

6) one (two) detected photon(s) in the case of DS (PS);

7) the difference of the energy depositions in LKr and tagging system <2.5 σ.

The decomposition of the events is given in Table 2. The experimental and the corresponding theoretical data on DS and PS are shown in Fig. 2 and 3 (For PS only a part of data is processed). As it is seen there is a satisfactory agreement between them. Thus, the application of fine experimental methods allowed observing PS. However, as in the case of multiply confirmed DS the results on PS need new measurements.

3. EXPERIMENTS ON NONLINEAR COMPTON AND INELASTIC LIGHT BY LIGHT SCATTERING

Many proposals have been published (see [38]). The experiments (Collaboration Princeton-Rochester-SLAC-Tennessee) have been caried out using the SLAC FFTB with ε = 46.6 GeV and a Nd: glass T^3 laser providing η = 0.4 and 0.32 at λ = 1053 (IR) and 527 nm (green) or Y = 0.26 and E^{*max}= 5.10^{15} V/cm in the electron rest frame.

a) Methods of measurements

1) In the case of Compton scattering (5) together with the usual method of measuring the spectra of the scattered photons with the help of pair spectrometer the authors obtained better results detecting the recoil electrons the calculated spectra of which are shown in Fig. 4 for 5.10^9 electrons at η = 0.6. This is because there are ~10^6 scattered photons per pulse for n=1 in (5), while the number of low energy scattered electrons for n>1 is very small. The minimal energy of the scattered electrons is given by

$$\varepsilon'_{\min}(n,\eta) = \frac{\varepsilon}{1+2n(1+\cos\alpha)}\frac{1}{m^{*2}}$$

where $m^* = m(1+\eta^2)^{1/2}$ is the electron effective mass, $\alpha = 17^0$ is the crossing angle. The main background comes from the plural Compton scattering, (n ω)+e → e' + (mω) (n>m, see Fig. 4), which is estimated by the pseudo photon method.

2) In the case of Breit-Wheeler process (6) the minimal number of the laser photons is given by

$$n_{\min}(\varepsilon_\gamma,\eta) = \frac{2m^2c^4(1+\eta^2)}{\hbar\omega\,\varepsilon_\gamma(1+\beta\cos\alpha)}.$$

b) The experimental arrangement

shown in Fig. 6 had the following parameters:

1) The laser beam had frequency f = 0.5 Hz, intensity after focusing on an area $A=2\pi\sigma_x\sigma_y = 30\ \mu^2$, length τ = 1.5 ps (FWHM), maximal

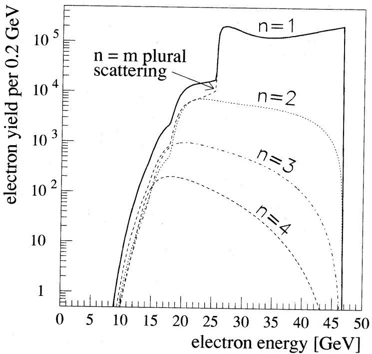

Fig. 4. Calculated *spectra of scattered electrons*

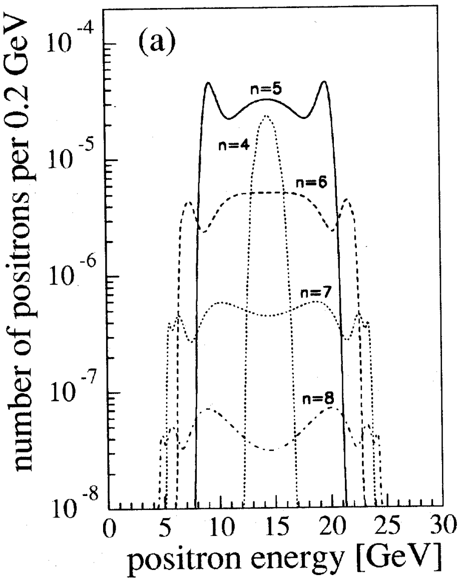

Fig. 5. *The* calculated *energy spectra of positrons for various n*

When in Compton scattering (5) n=1, then for ε_γ = 29.1 GeV no e^+ e^- pair can be produced (6) for n=1. If ε = 46.6 GeV, ђω = 2.34 eV and η = 0, then $n_{\min}$ = 5. In this experiment n = 4 also can give contribution due to η ≠ 0 and n=2 in (5). The calculated energy spectra of positrons produced in the collision of 30 GeV electron and 2.34 eV laser photon beams are shown in Fig. 5. Therefore the detection of ~10^{-3} positrons per pulse is the adopted method in this experiment.

I = 10^{16} – 10^{18} W/cm^2 providing η= 0.1-0.35.

2) The electron beam had f = 30 Hz, τ = 3.6 ps, σ_x =30 μ, σ_y =40 μ, σ_z = 1 mm and emitance ε_x = 3.10^{10} m·rad, ε_y = 3.10^{-11} m·rad.

3) The scattered electrons and positrons after a 6 magnet spectrometer were detected by Si (300 μ) and W (1 rl) sandwich calorimeters ECAL and PCAL having 1.6X1.6 cm^2 pads and sufficient energy resolution.

4) The energy of forward photons was measured by the calorimeter CCAL or sometimes by pair spectrometer with sufficient resolution.

c) Some experimental results

1) *Multiphoton Compton Scattering.* The dependences of the differential scattered electron yield normalized over incident photon number upon electron momentum and IR laser intensity are shown in Figs. 7 and 8, respectively.

In Fig. 7 the solid circles and open boxes are for measured and simulated results on multiple Compton scattering. The dashed curve is the simulation for n=m plural scattering. In Fig. 8 the experimental results (points with errors) at various momenta and n are compared with the simulation results (shadowed bands) and errors mainly due to 30% uncertainty of the laser intensity. There is a good agreement with the expected behavior ~$\eta^{2(n-1)}$ ~ I^{n-1}.

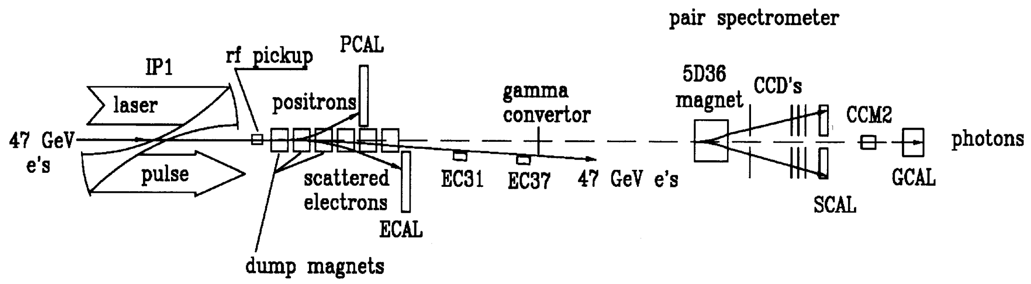

Fig. 6. The experimental set-up

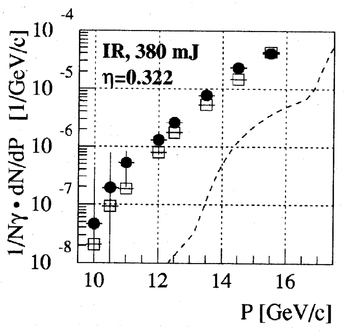

Fig. 7. The spectra of the scattered electrons

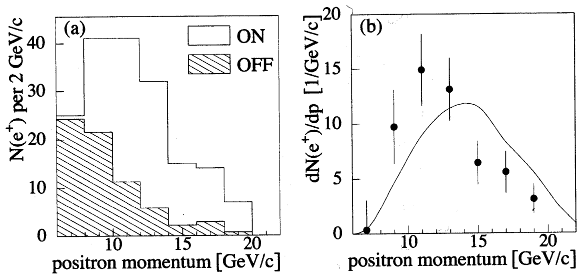

Fig. 9. The spectra of detected positrons

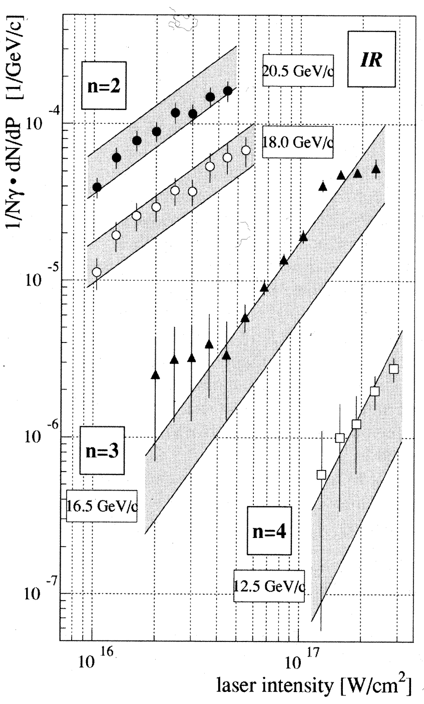

Fig. 8. The dependence *of the scattered electron yield on laser intensity*

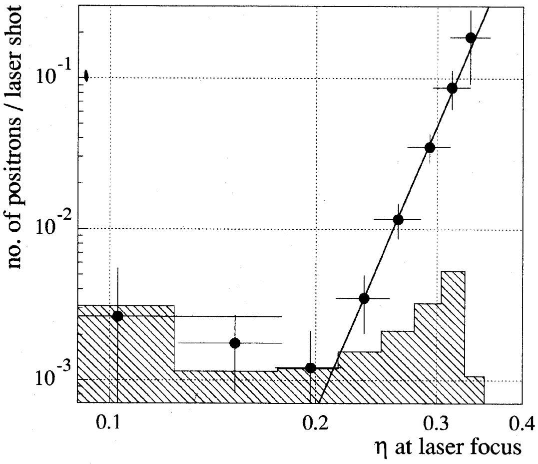

Fig. 10. The dependence of the positron yield on η

2) *Pair production in strong fields.* The detected positron spectra without and with laser and the simulated one are shown in Fig. 9, while the dependence of the positron yield on η is given in Fig. 10. As it is seen the detected positron spectra are in agreement with the simulations, while the observed yield is ~ $\eta^{2n}_{\min}$ with $n_{\min}$ = 5.1 ± 0.2 ± 0.5/0.8 where the first and second errors are the statistic and systematic errors mainly due to the η measurement.

These shortly described Novosibirsk and SLAC experiments showed how difficult will be the advance in this direction.

4. NEXT GENERATION QED NONLINEAR EFFECT EXPERIMENTS

After closing LEP2 for which there was a project [39] the following nonstudied experiments can be performed on future 250 – 2000 GeV linear $e^+ e^-$ colliders such as TESLA [40].

a) Elastic and Inelastic Light Scaattering by Light

As it has been shown still in 1963 [5] considering xperiments on the reactions (1) and (6) for n ≥1 with similar kinematics one must take into account that 1) for (1) the cross section has maximum when the photon energy in cms $(\omega\varepsilon_\gamma)^{1/2} \approx mc^2$, 2) the minimal scattering angle must be larger than the collimation angles of the high energy photon and 3) the cross section integrated from this minimal angle is $\sim\omega_{3sc}/\varepsilon_\gamma$. One can consider three options of photon-photon collisions on TESLA at 250 GeV (see the schemes of Fig. 11). For parameters of the laser beams used in [22] and the expected electron, secondary SASE x-ray and γ-beams [40] the estimated rates of the detected events of the reaction (1) is one per 10 – 10^4 laser pulses.

b) Unruh Effect (Radiation)

According to the Unruh Effect (see the review [29]) any particle moving with a acceleration g' in its 'instantaneous rest frame finds itself in a bath of black body radiation with a temperature

$$T = \frac{\hbar}{2\pi ck} g',$$

which is similar to the Hawking formula with k being the Boltzman constant. Of many proposed tests of this effect we remind only the high energy radiation experiment (see [29]. Using Plank's formula and considering Compton scattering of the both photons on high energy electrons one can show that the produced Unruh radiation, which is $\sim g'^4$, will exceed the usual Larmor radiation, which is $\sim g'^2$, when $g' > g'_{crit} = 3.10^{33}$ cm/s^2. If such a g' is achieved by E, then it must be one order of magnitude beyond the QED critical $E_0 = 1.3.10^6$ V/cm. Since relativistic particles "feels" the external fields enhanced γ times the Unruh effect can be observed having such fields or the field of single crystal in case of channeling and using electrons with energies higher than 200 GeV. It is necessary to separate the Unruh radiation from the other usual "Larmor type" synchrotron or channeling radiation.

c) Field induced variation of index of refraction and vacuum Cherenkov radiation

For magmetic fields with $F \ll F_0$ and perpendicular to the photon propagation direction the index of refraction of vacuum varies as

$$n(\omega) = 1 + \frac{\alpha}{\pi}\left(\frac{F}{F_0}\right)^2 \left[N(\chi) + i\pi\,\frac{T(\chi)}{2\chi}\right]$$

where $\chi = (\hbar\omega/mc^2)(F/F_0)$. The functions N(χ) and T(χ) are calculated in [30]. Neglecting the imaginary part, one can show that the threshold value of a circularly polarized field when an electron with Lorenz factor γ begins to produce vacuum Cherenkov radiation is given by

$$E_{thr} = \frac{1}{\gamma}\left(\frac{45\pi}{22\alpha}\right)^{1/2} E_0 = \frac{1}{\gamma} 29.7 E_0 .$$

For a 250 GeV electron $E_{thr} \approx 8.10^{11}$ V/cm or $I \approx 8\cdot10^{21}$ W/cm^2 (in more detail see [38]).

Thus, even without considering the fine physics of the processes (1)-(10) one can be sure that the future technology and methods will allow to decrease the regions "not observed' in Table 1.

The author thanks I.I. Goldman, V.A. Khoze, A.I. Nikishov and V.I. Ritus for discussing the above problems since 1963 and N.F. Shul'ga for inviting to this conference.

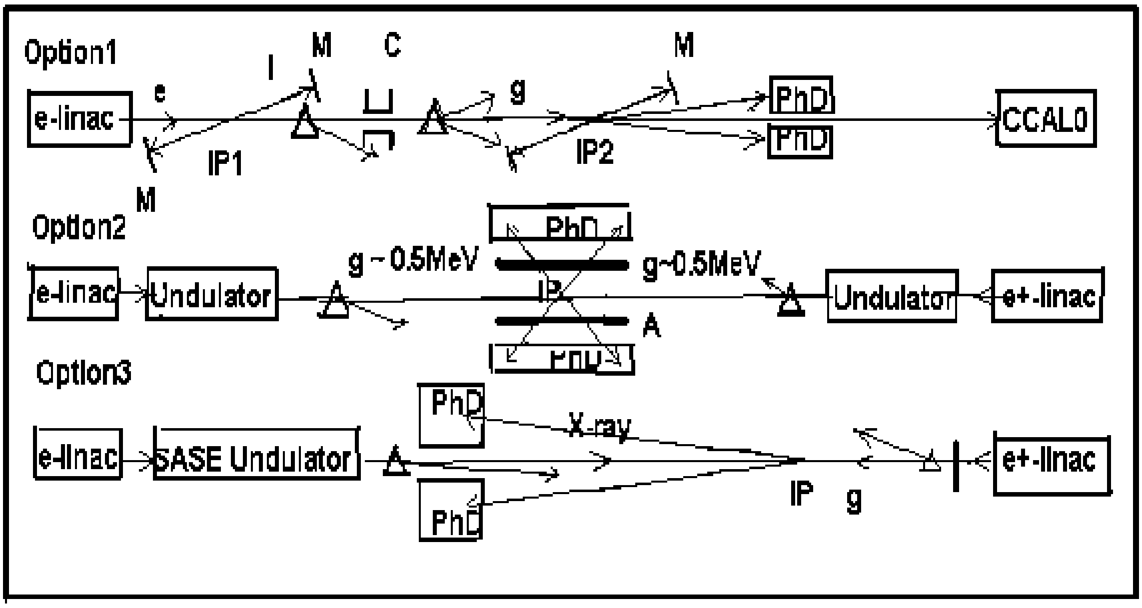

Fig. 11. *Light by light scattering experiments on 250 GeV ee-collider. For options 1, 2 and 3* $\varepsilon_\gamma >> \omega$, $\varepsilon_{\gamma 1} \approx \varepsilon_{\gamma 2} \approx mc^2$ *and* $\varepsilon_{\gamma 1} \approx$ *10 KeVand* $\varepsilon_{\gamma 2} \approx$*25 MeV. l,x-ray and g are for light, x, γ-quanta*

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