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A PROPOSAL FOR OBTAINING AND MEASURING THE POLARIZATION OF POLARIZED BEAMS OF GAMMA QUANTA AT ENERGIES $\omega>200$GeV PRODUCED BY PLANARLY CHANNELED ELECTRONS

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ՀԱՐԹ ԿԱՆԱԼԱՑՎԱԾ ԷԼԵԿՏՐՈՆՆԵՐԻ ԱՌԱՋԱՑՐԱԾ ω>200 ԳէՎ ԷՆԵՐԳԻԱՅՈՎ ԳԱՄՄԱ-ՔՎԱՆՏՆԵՐԻ ԲԵՎԵՌԱՑՎԱԾ ՓՆՋԵՐԻ ԲԵՎԵՌԱՑՄԱՆ ՍՏԱՑՄԱՆ ԵՎ ՉԱՓՄԱՆ ԱՌԱՋԱՐԿՈՒԹՅՈՒՆ

Օգտագործելով փսևդոֆոտոնային ճառագայթման բանաձևերը, հաստատուն դաշտի մոտավորությամբ հաշվված է բյուրեղային հարթություններում կանալացված մեծ էներգիայի էլեկտրոնների առաջացրած ֆոտոնային փնջերի բևեռացումը 100ԳէՎ-ից ավելի էներգիայով ֆոտոնների համար քննարկված են բևեռացման չափման մի քանի մեթոդներ։ Առաջարկված է փորձարարական սարքերի սխեմա՝ այդ էներգիաների ժամանակ բևեռացված ֆոտոնների փնջեր ստանալու և վերահսկելու համար։

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1. Introduction

The radiation of channeled particles (RCP) is a promising method for obtaining high energy γ-quanta beams. At present the spectral distribution of RCP is measured up to few hundred GeV [1]. However, besides the results of the work [2] obtained at electron energy E_e=1GeV and $x=\omega/E_e=10^{-2}$ (ω is the photon energy, $\hbar=c=1$), there are no theoretical and experimental data on the polarization of RCP. Nevertheless, it is not difficult to show that RCP has a high degree of polarization, though not 100%, but sufficiently high to find a wide application in elementary particle and nuclear physics like the coherent bremsstrahlung photon beams did. Indeed, as it is well known, at energies when the constant field approximation is valid [3], synchrotron radiation (SR) is the main mechanism for RCP production. On the other hand, it is well known [4,5] that in the case of two-dimensional particle motion (planar channeling) SR has a high value of linear polarization $P_l=|\vec{P}_l|$ in the whole frequency region, the SR photon electric vector lying in the trajectory plane. In the classical limit when the SR parameter $\Upsilon=\gamma H/H_c \ll 1$ ($\gamma=E/m$ is the Lorentz factor of the particle with mass m, H is the external field, and $H_c=m_e^2/c=4.41\ 10^{13}$g is the so-called critical field), the integrated over all frequencies and angles $P_l=3/4$, while in the quantum limit when $\Upsilon \gg 1$,

P_1=9/32. Therefore, one may expect for RCP also a high degree of polarization since separate parts of the trajectories at RCP and SR are similar to each other.

However the theoretical model [3] is an approximation and though it provides good results which are in agreement with the experimental data on the spectral distribution almost for all values of x of RCP, nevertheless one can not say that polarization calculations carried out by the SR formulae [4,5] using the model [3] are quite right. It is necessary to take into account the parameter L of the model [3], fitted to the experimental data and introduced into calculations since the trajectories in the case of channeling are not circular as in the case of SR. The parameter L is especially important in the region of low frequencies when the formation length is relatively large relative to the trajectory period and it is necessary to cut the SR integrals at ~L/2. Such a calculation technique is similar to the radiation integral cutting method [6] developed for the semiclassical description of the Landau-Pomeranchuck-effect. For this reason one must carry out polarization measurement or check the calculation results by more accurate calculations with the help of correct theories such as described in [5].

On the other hand the widely spread methods of polarization measurements [7-9] are either very difficult or simply not applicable when ω>100GeV. For this energy region there are some new suggested but not verified methods for the measurement of the linear P_l [10-12] and circular P_c [12] polarization. The old methods [7-9] are used for the measurement of P_l of coherent bremsstrahlung of electrons with E_e up to some tens of GeV almost for all values of x (see [13]). The measured values of P_l are in agreement with the theoretical predictions (see [14]).

For the polarization measurement of RCP the method of deuteron disintegration suggested in [15] was iniatially used [16]. Then a Compton polarimeter has been used for the same purpose [2]. The result of the works [2,16] $P_l \approx 0.6$ is in agreement with the predictions obtained in [2] by particle trajectory modeling and averaging the Stocks parameters over various trajectories. As it was mentioned above at present there are neither measurements nor theoretical calculations of P of RCP at energies above 1GeV.

Taking into account the above described situation in this work first we calculate P of RCP by the simplest method. The obtained results show that there is a sufficiently high value of P_l in a wide region of x. Of course, due to the accepted assumptions the obtained results need in verification by more accurate calculations and experimental measurements especially before using the produced photon beams. For this reason we then analyze the already suggested methods and propose new methods for measuring P. And finally we consider an experimental arrangement which can provide polarized photon beams for various high energy experiments.

2. Method and Results of the Polarisation Calculation

For the physics and application limits of the constant field approximation method referring the works [3,5] we shall simply consider the motion of an electron (or a positron) in the crystallographic field which in the case of planar channeling may be described by parabolic potential

$$V(y) = V_0 y^2, \tag{1}$$

where Vo is the depth of the potential well, $y=z/(d_p/2)$ is the dimensionless distance of the particle from the well symmetry plane, d_p is the distance between two adjacent crystallographic axes. The moving electron feels an electric field $E(y)=-2V_0 y/e/(d_p/2)$. The corresponding SR parameter is equal to

$$\Upsilon = \gamma \frac{E}{E_c} = 4\gamma \frac{V_0}{m} \frac{\lambda_e}{d_p} y = 3.02\ 10^{-8} \frac{V_0(eV)}{d_p(Å)} y, \tag{2}$$

where λ_e is the electron Compton length, $E_c=m^2/c$ is the critical field.

According to the SR quantum theory [3,5] the spectral distribution of the emitted SR after integration over the angles is given by the formula

$$\frac{dI_i}{d\omega} = \frac{xd^2N_i}{dtdx} = \frac{e^2m^2x^2}{2\pi\sqrt{3}E_e} \left\{ -\int K_{1/3}(s)ds + [2-(-1)^i + \frac{x^2}{1-x}]K_{2/3}(u) \right\}. \tag{3}$$

In the expression (3) i=1 and 2 are for SR polarizations with electric vectors parallel and perpendicular to the trajectory plane, $K_{1/3,2/3}(v)$ are the McDonald's functions and

$$u = \frac{2x}{3Y(1-x)} .$$

As it is seen from the formulae (1) and (2) the field which the moving particle feels depends on the particle distance from the crystallographic planes. Therefore, in order to calculate the intensity of the RCP, it is necessary to average the expression (3) over the y distribution function $dW(y)/dy$ and take into account the fraction D of the channeled particles. The functions $dW(y)/dy$ and D are investigated in the work [17].

After averaging the expression (3) over y it is easy to obtain the following expression for the degree of polarization of RCP:

$$P = \frac{\frac{dI_1}{d\omega} - \frac{dI_2}{d\omega}}{\frac{dI_1}{d\omega} + \frac{dI_2}{d\omega}} = \frac{\int_0^1 dW(y) K_{2/3}(u(y))}{\int_0^1 dW(y) \left\{ - \int_{u(y)}^{\infty} K_{1/3}(s)ds + \left[2 + \frac{x}{1-x}\right] K_{1/3}(u(y)) \right\}} . \quad (4)$$

Before presenting the results of the numerical calculations with the help of the formula (4) let us discuss in short some approximations and assumptions made for its derivation and its application limits. First, the formula (4) is applicable for energies higher than certain ones E_{cfa} when the constant field approximation is applicable. Without giving the details (see [3,5]) let us note that for the planes (110) E_{cfa}=20.5;19.0;10.9 and 4.5GeV for diamond (C), silicon (Si), germanium (Ge) and tungsten (W) crystals, respectively. Second, let us remind that the multiple scattering (dechanneling) as well as the crystal imperfectness are not taken into account in the constant field approximation [3,5] and during the derivation of the $dW(y)/dy$ [17]. Therefore,one may use the formula (4) for thin crystal without defects. Third, it is assumed that the above mentioned parameter L of the model [3] does not influence the polarization calculations, or L reduces equally the both SR amplitudes of mutually perpendicular polarizations.

It would be also noted, that one can not expect any circular polarization for the radiation of nonpolarized channeled particles since the corresponding Stocks parameter is equal to zero. The production of the circularly polarized photon beams by angular collimation in the case of axial channeling or with the help of polarized electrons in crystals seems to be unreasonable.

Figs. 1 and 2 show the dependence of P_1 on $x=\omega/E_e$ calculated with the help of the formula (4) for the radiation of electrons channeled in the planes (110) of diamond (C) and tungsten (W) crystals at various electron energies, respectively. Th calculations have been carried out for particle beams entering the crystal under an angle $\theta_{ent}=0$ and having an angular spread $\theta_{spr}=0$. As it is shown in [17] in this case $D\approx1$, while t distribution function has the form

$$\frac{dW(y)}{dy} = \frac{1}{\pi} \ln \frac{1 + \sqrt{1-y^2}}{y} . \qquad (5)$$

As it is seen from Fig.1 and 2, in agreement with the above mentioned property of SR the values of P_1 slowly decreases when the particle energy increases from 20 to 1000GeV. The maximum of the curves $P_{max} \approx 0.9$ at $x \approx 0.15$ is shifted to $P_{max} \approx 0.65$ at $x \approx 0.3$. At all energies one has a sufficiently high degree of polarization up to $x \approx 0.75$. The calculations carried out for various monocrystals and particles show that the account of $dW(y)/dy$ changes the values of P_1 by 5-10% (increase in the case of negative particles).

3. Methods for the Measurement of Polarization

All the suggested methods for the measurement of P use theoretically studied processes, mainly quantum electrodynamical processes, and are characterized by the so-called analysing ability:

$$R = \frac{\sigma_{\parallel} - \sigma_{\perp}}{\sigma_{\parallel} - \sigma_{\perp}} , \qquad (6)$$

where $\sigma_{\parallel,\perp}$ are the processes cross sections when the primary photons are polarized parallelly or perpendicularly to a certain plane (crystallographic, reaction or other plane). Since at energies $\omega > 100$GeV the characteristic angles become very small, the usual methods of measurement of P appear to be impractical. For this reason below we shall briefly describe suggested but not realised methods and propose new methods.

<u>a) The method using the recoil electron asymmetry in the reaction $\gamma e \rightarrow eee$ [10]</u> will be realised by an arrangement [18] which can be described as follows. The γ-quanta beam produces

e^+e^--pairs on the target electrons through which it passes. The high energy pair is detected by scintillation counters downstream in coincidence with the recoil electron with energies up to tens MeV. Some telescopes consisting of dE/dx, range and anticoincidence counters and placed around the target allow to measure the recoil electron energy and azimuthal distribution which is connected with the photon polarization by the relation

$$2\pi \frac{d\sigma}{d\varphi} = \sigma_0[1 - |\vec{P}|R\cos(2\varphi)], \qquad (7)$$

where σ_0 is the total cross section of the process, while φ is the azimuthal angle between $\bar{P}_1$ and recoil electron momentum. At ω>1GeV

$$R = \frac{(4/9)\ln(2\omega/m)-20/28}{(28/9)\ln(2\omega)-218/27}, \qquad (8)$$

which is equal to R=0.154 at ω=100GeV and R→0.143 when $\omega\to\infty$. Unfortunately this promising method is not applicable for circularly polarized photons.

b) The method using polarized laser photon beams in the reaction [12] $\gamma\gamma\to e^+e^-$ is technically more difficult. However, it provides greater values of R which is important in the case of low values of P. It is also applicable for circularly polarized photons. In this method the γ-quanta beam the linear (circular) polarization of which we want to measure collides with an intense oncoming laser beam with polarization parallel and perpendicular (with the same and opposite helicity). Due to the large difference between the corresponding cross sections $\sigma_{\parallel,+}$ and $\sigma_{\perp,-}$ ($\sigma_{+,-}$ are the cross sections for colliding photons with the same and opposite helicities, respectively) the detectors of e^+e^--pairs placed downstream after a sweeping magnet will detect various numbers $N_{\parallel,+}$ and $N_{\perp,-}$. The degree of the polarization is determined by the formula:

$$P_{l,c} = \frac{1}{R} \frac{N_{\parallel,+} - N_{\perp,-}}{N_{\parallel,+} + N_{\perp,-}} . \tag{9}$$

Using the formulae of the work [19] it is shown [12] that this method provides values of R close to 1. Though this method is the only method allowing to measure circular polarization and providing high values of R and of the so called reduced analyzing ability σR^2, nevertheless, it is required high laser beam intensities, since the densities of the laser targets are much lower than that of even gaseous targets. The threshold property of the reaction $\gamma\gamma \to e^+e^-$ is an another drawback of this method:in the case of a neodymium laser with λ=1.05 μm the threshold energy of the γ-quanta is ω_{thr}=140GeV.

c)The method using the birefringence properties of crystals. Following the work [8] the authors of [11] develop the method of obtaining polarized photon beams at energies ω>100GeV using the fact that when the entering angle of γ-quanta into crystal $\theta_{ent}<\theta_{Lind}$ (θ_{Lind} is the Lindhard angle) the e^+e^--pair production cross section strongly depends on the angle between the crystallographic plane and the γ-quanta linear polarization. It is not difficult to show that the same birefringence property of crystals can be used for the measurement of P_l. Indeed, let a γ-quanta beam with initial intensity $I(\omega,0)$ and polarization $P_l(0)$ passes through a crystal one of the crystallographic planes of which, say (110), makes an angle φ with the vector $\vec{P}_l(0)$. Then after a thickness t the relative reduction of the beam intensity will be

$$\left[\frac{I(\omega,t)}{I(\omega,0)}\right]_{P_l(0)}=\left[\frac{I(\omega,t)}{I(\omega,0)}\right]_{P=0}[1+|\vec{P}_l(0)|th(RWt)\cos(2\varphi)] \quad , \qquad (10)$$

where the first factor in the right hand side of (10) is the reduction of the unpolarized beam, $R=(W_\perp-W_\parallel)/(W_\perp+W_\parallel)$; $W=(W_\perp+W_\parallel)/2$; W; $W_{\perp,\parallel}$ are the absorption coefficients for unpolarized and polarized beams respectively(for R, W, $W_{\perp,\parallel}$ see [11]). As it is shown in [11] R increases with ω, and $R\to1/3$ when $\omega\to\infty$.

Now let us consider three methods for the measurement of $P_\perp$ two of which follow directly from formula (10).

i) The method of a single thick crystal. Let a linearly polarized beam of γ-quanta with known direction of $\vec{P}_l$ (remember that if the beam is obtained by the method described in the second section of this work the polarization direction coincides with the direction of the corresponding crystallographic plane) and intensity $I(\omega,0)$ passes through a crystal analyzer with thickness t. It is necessary to measure after the crystal the intensities $I_\perp(\omega,t)$ and $I_\parallel(\omega,t)$ at two crystal orientations when a certain crystallographic plane, say (110), is parallel and perpendicular to the direction of $\vec{P}_l$. Then it follows from expression (10)

$$P_1 = \frac{r-1}{r+1}\,\frac{1}{\mathrm{th}(RWt)}\,, \tag{11}$$

where $r=I_\perp(\omega,t)/I_\parallel(w,t)$. Thus, measuring $I_{\perp,\parallel}(\omega,t)$ one determines r and using the theoretical values of R, W, $W_{\perp,\parallel}$ [11] determines P_1 with the help of (11).

ii) The method of two thick crystals .In this case it is necessary to determine r_1 and r_2 by the method described in i) using four measurements in two crystals with thicknesses t_1 and $t_2=2t_1$. Then the polarization can be determined by the following expression:

$$P_1 = \left[2\,\frac{r_2+1}{r_2-1}\,\frac{r_1+1}{r_1-1} - \left(\frac{r_1+1}{r_1-1}\right)^2\right]^{-1/2} . \tag{12}$$

The advantage of this method is that in order to determine P_1 one does not need the theoretical values of R, W and $W_{\perp,\parallel}$ the calculation of which is connected with various approximations and difficulties [5,11].Of course the methods i) and ii) can be used also for lower energy photons with the help of coherent bremsstrahlung taking corresponding planes, R etc.

iii) The method of a single thin crystal. This is the high energy modification of the method [9] which by coherent bremsstrahlung at energies up to few tens of GeV provides values of R=0.16-0.26 for a narrow region of energies of symmetrical pairs (see, for instance [13,14]).

As it has been already mentioned above at energies $\omega>200$ GeV in the condition of channeling one has sufficiently high values of R for all the energies of e^+ and e^- particles, so that there is no need to choose the symmetrical pairs. In this method the polarization is determined by the following well known formula:

$$P = \frac{1}{R} \frac{N_{\perp}-N_{\parallel}}{N_{\perp}+N_{\parallel}} , \tag{13}$$

where $N_{\perp,\parallel}$ are the numbers of the detected $e^{+}e^{-}$-pairs produced in a thin crystal when a certain crystallographic plane is oriented perpendicularly and in parallel to the γ-beam polarization. Of course, this is the simplest method of determination of P_1, but it requires the knowledge of the theoretical value of R. Therefore, it is desirable to check the results once by the method ii) which does not require any theoretical value.

4. The Proposed Experimental Arrangement

Fig. 3 shows schematically the experimental arrangement which is necessary for the realization of the present proposal for the production of polarized photon beams at ω>200GeV for different high energy experiments. A beam of electrons with E_e>300 GeV and angular spread less than the corresponding Lindhard angle passes through crystal-polarizer T_1 placed in the goniometer Γ_1. The entering angle of the beam with respect to a certain crystallographic plane, say (110), is θ_{ent}=0. It is necessary to choose such a polarizer thickness that excludes multiple (pile-up) effects, i.e. much less than the electron dechanneling length. A diamond crystal with thickness less than

100μm is a good polarizer. After the sweeping magnet M_1 the γ-beam has intensity $dI(0)/d\omega$ and linear polarization P_0 parallel to the normal to the plane (110) of the polarizer T_1. In the first approximation the degree of polarization can be calculated by the formula (4).

One can measure the polarization with the help of i) a single thick , ii) two thick and iii) a thin crystals T_2 placed in the goniometer Γ_2 with two orientations perpendicular and parallel to $\vec{P}_0$.

i) It is reasonable to choose a tungsten crystal as a single crystal analyzer T_2 since, as it follows from the calculations [11] for tungsten, the crystallographic effect dominates over the background Bethe Heitler pair production process at relatively low energies about $\omega>300$GeV and the relevant crystal thicknesses are less than 1cm. Indeed, using the formula (11) one can show, that the optimal analyzer thickness t_{opt}, when the beam intensity reduction and the polarization measurement errors are reasonable, is determined from the condition $t_{opt}RW\simeq1$. Using the results of [11] one can show that at $\omega>500$GeV when the contribution of the Bethe Heitler pair production is small and $R\simeq1/3$ $(W_{\perp}=2W_{\parallel})$, one obtains $t_{opt}=0.08$cm, and if $|\vec{P}_0|\simeq0.5$, $r\simeq1.6$ and the beam intensity decreases ~3.6 and ~5.8 times after the analyzer for parallel and perpendicular orientations, respectively.

Thus, the determination of $|\vec{P}_0|$ with the help of the formula [11] is brought to the measurement of the spectra after the crystal analyser in two orientations with the help of a NaI(Tl) spectrometer located after the sweeping magnet M_2 and anticoincidence scintillation counter C.

ii) In the case of two thick crystal method it is necessary to add to the above described measurements similar two measurements after a tungsten crystal with double thickness t_2=0.16cm. $|\vec{P}_0|$ is determined with the formula (12). Again using the results of [11] one obtains: $r_2 \approx 2.2$ and the beam intensity decreases ~14 and ~32.4 times for parallel and perpendicular orientations, respectively.

iii) In the case of the determination of $|\vec{P}|$ with the help of the formula [13] of the method of a thin crystal the sweeping magnet M_2 is switched out, the counter C is in coincidence, and one measures the number of the produced pairs $N_\perp$ and $N_\parallel$ for two orientations of the crystal analyzer which is better to be a ≤1/20 radiation length diamond.

In conclusion one may resume that at SPS, Tevatron and future SSC, UNK and linear colliders the presence of the electron beams with energies E_e>300GeV allow to obtain photon beams with measured spectrum and linear polarization. In comparison with the method of coherent bremsstrahlung [13,14] in the case of RCP one has a sufficiently high degree of polarization in a wide photon energy region (this is an advantage). However, the photon beam in the case of RCP is not quasimonochromatic, which is not always a drawback, if one takes into account the difficulties of crystal orientation necessary at every photon energy in case of coherent bremsstrahlung. The linear polarization can be converted into circular one with the help of a quarter-length plate which presents itself a $t_{\lambda/4} \simeq 0.4$ cm thick tungsten crystal for $\omega > 300$GeV [11]. At present new more accurate calculations on the polarization are in progress. We think that they will change the results presented in this work slightly. Therefore, it is the time to begin the above proposed nuclear-optical experiments to provide high energy experiments with polarized photon beams.

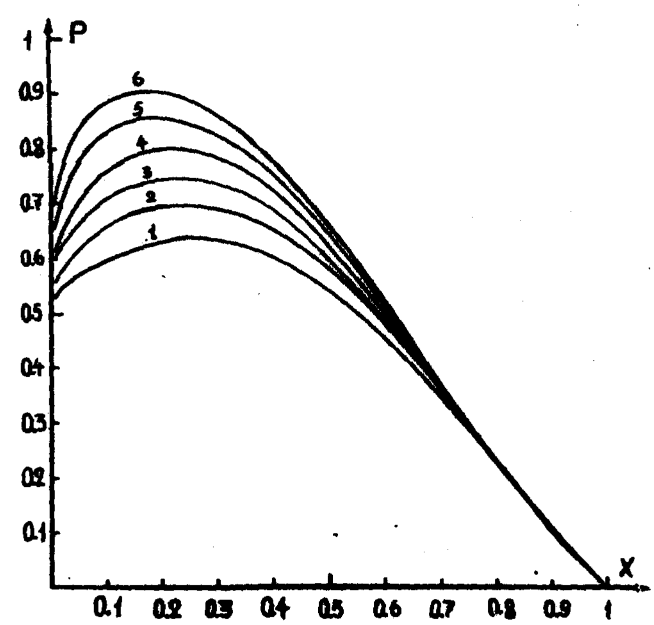

Fig.1

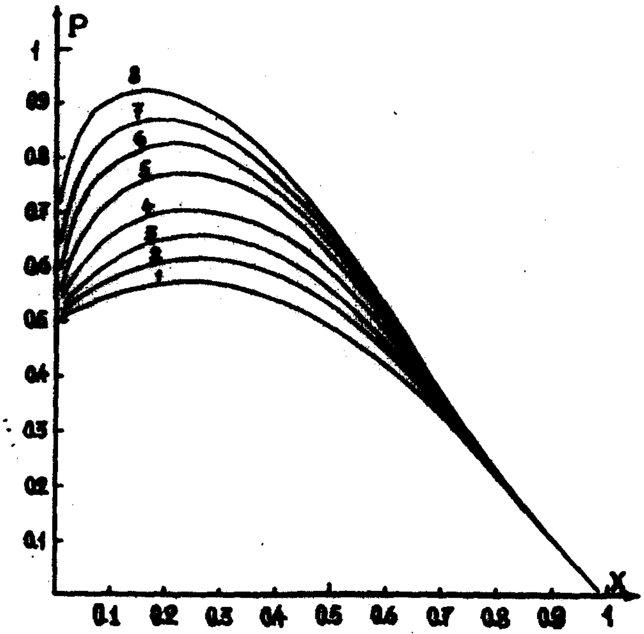

Fig.2

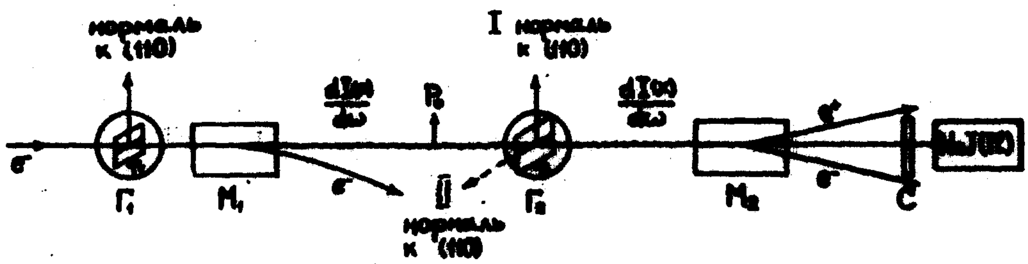

Fig.3

Figure captions

Fig.1. The dependence of the linear polarisation P_l on $x=\omega/E_e$ for the radiation of electrons channeled in the diamond crystal plane (110). The curves 1, 2, 3, 4, 5 and 6 have been calculated by the formula (4) for electron energies E_e= 1000, 400, 200, 100, 40 and 20 GeV, respectively.

Fig.2. The dependence of the linear polarisation P_l on $x=\omega/E_e$ for the radiation of electrons channeled in the tungsten crystal plane (110). The curves 1, 2, 3, 4, 5, 6, 7 and 8 have been calculated by the formula (4) for electron energies E_e= 1000, 400, 200, 100, 40, 20, 10 and 4GeV, respectively.

Fig.3. The experimental arrangement. $\Gamma_{1,2}$ are goniometers, $T_{1,2}$ are crystal targets, $M_{1,2}$ are sweeping magnets, C is a scintillation counter, NaI(Tl) is a total absorption spectrometer.

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ПРЕДЛОЖЕНИЕ ДЛЯ ПОЛУЧЕНИЯ И ИЗМЕРЕНИЯ ПОЛЯРИЗАЦИИ

ПОЛЯРИЗОВАННЫХ ПУЧКОВ ГАММА КВАНТОВ С ЭНЕРГИЯМИ ω>200ГэВ,

ОБРАЗОВАННЫХ ЭЛЕКТРОНАМИ ПРИ ПЛОСКОСТНОМ КАНАЛИРОВАНИИ

(на английском языке, перевод К.А.Испиряна)

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