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Methods for the measurement of the refractive index of MeV photons using total internal and external reflection

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Abstract. Recently it has been theoretically and experimentally shown that for 1–10 MeV and 1–2 MeV photons, respectively, the refractive index of Si is greater than 1. Taking into account the difficulties of the carried out experiment it is proposed to measure directly the refractive index of Si and other materials detecting the total internal and external reflections.

1. Introduction

Up to the publication of the results of the work [1] it was accepted that in the gamma ray energy region of photons with energy \( \hbar \omega > 1 \text{ MeV} \) the real part of the refractive index \( n = 1 + \delta \) of all the materials is less than 1, \( n(\omega) < 1 \), and is given by the formula

\[
n(\omega) = \sqrt{\varepsilon(\omega)} = 1 + \delta(\omega) \approx 1 - 0.5(\omega_p / \omega)^2
\]

where \( \varepsilon(\omega) \) is the real part of the dielectric constant, \( \omega_p \) is the plasma frequency, and, therefore, \( \delta(\omega) < 0 \). The sensational experimental results of [1] have been obtained only for photon energies 0.786, 1.165 and 1.951 MeV in a very difficult experiment measuring the nanoradian deflection of very monochromatic gamma beams with very small angular spread. The experiment has been carried out at Institut Laue-Langevin (ILL) on the facility GAMS5 [2] using a double crystal Bragg diffraction spectrometer. Experimentally it has been shown [1] that for the above energies \( n(\omega) > 1 \) with measured values \( \delta \approx (10^{-10} - 10^{-9}) \).

The authors of [1] carrying out complicated non-perturbative QED calculations explained their observations with the help of QED nonlinear process of Delbruck scattering which as the photon-photon scattering takes place by virtual electron-positron pair production. A comment [3] on the work [1] has been sent in September 2012 and published in March 2013 in which it has been shown that even using the Delbruck scattering cross sections given in [1] the contribution of Delbruck effect into \( \delta \) is \( 10^6 - 10^5 \) times less than it was estimated in [1]. The most amazing fact is that there is a good agreement between the theoretical and experimental results of [1].

The discovery of [1] is of fundamental importance because it opens new possibilities and directions in gamma optics, nuclear physics, etc [4–7]. Therefore, a problem in physics of the XXI century is present. It is more reasonable to solve the above described problem experimentally. Taking into account that the methods of [1] are very difficult we have carried out transparent calculations on a new phenomenon of gamma ray Cherenkov-transition radiation (GCTR) and proposed [8] a much simpler experiment. The observation and study of GCTR can confirm or decline the fundamental discovery of [1].

In this short note it is discussed and proposed a direct method for the measurement of \( n(\omega) \) of various materials using total external reflection (TER) and total internal reflection (TIR). The advantages of the proposed method compared with the method of [1] are: 1) there is no need of very...
monochromatic MeV photons and high detection energy resolution and 2) instead of nanoradian accuracies of [1] only microradian accuracies of angles are enough. The first advantage is due to the fact that despite to the regions around K-, L- edges $n(\omega)$ in MeV region varies slowly. The second advantage is connected with the absence of Bragg diffraction spectrometers.

2. Method of Using TIR and TER for the Measurement of $n(\omega)$ in MeV Region

It is well known that if $n(\omega)>1$ (optical and softer region), and the photons intersect the boundary medium-vacuum, it can take place total internal reflection, if the incidence angle, $\theta_{inc}=\pi/2-\theta_{gl}$ ($\theta_{gl}$ is the glancing angle) is greater than a critical angle $\theta^{TIR}_{cr}=\arcsin(1/n)$. Similarly, if $n(\omega)<1$ (X-ray and harder region), and the photons intersect the boundary vacuum-medium it can take place total external reflection if the glancing angle, $\theta_{gl}$, is less than a critical angle $\theta^{TER}_{cr}=(2\delta)^{1/2}$. In order to use TER (or TIR) for the direct measurement of $n(\omega)$, and to show: is $n(\omega)>1$ or $n(\omega)<1$ for MeV photons, it is proposed the arrangement and method shown in figure 1.

![Figure 1. The proposed experimental arrangement (without collimators and shielding) and method.](image)

As it is seen in figure 1 a photon beam with energy 1–10 MeV and with not small energy resolution (of the order of up to $\Delta\omega/\omega \sim 10\%$) and angular spread, much less than the spread of the photon beam from the inverse Compton scattering source (see below), strikes a flat silicon (Si) reflector shown in figure 1. When it is expected that $n(\omega)>1$ the flat reflector of the figure 1 is used. When it is expected that $n(\omega)<1$ the table shape Si target shown in the insert “1” is used. In the case of the flat Si reflector the photons are undergone TER, if the glancing angle is less than $\theta^{TER}_{cr}$. The photons pass through the reflector, if the glancing angle is greater than $\theta^{TER}_{cr}$. In the case of the table shape Si reflector the photons enter freely the solid silicon, reach the bottom boundary between the silicon and vacuum, undergo TIR and come out of the reflector, if the incidence angle is large than $\theta^{TIR}_{cr}$. The photons pass through the table shape reflector if the incidence angle is less than $\theta^{TIR}_{cr}$. The photons passing through the reflectors are detected with the help of transmitted photon detector, while the photons undergoing TER or TIR are detected by the reflected photon detector. Both the transmitted and reflected photon detectors measure the energy of the photons with not very good (as in [1]) resolution. The angular spread of the photons from the source is $\theta_{rad}=1/\gamma$, where $\gamma=E/mc^2=1/[1-(V/c)^2]^{1/2}$ is the relativistic factor of the inverse Compton scattering electrons. The reflectors are placed at a distance $L$ from the source and have longitudinal and transversal sizes $T$. The reflected photon and
transmitted photon detectors detect the photons only in an acceptance angular interval \( \theta_{acc} \ll \theta_{rad} \). Therefore, only a small fraction \( F = (\theta_{acc} / \theta_{rad})^2 \approx (T_0 \gamma / 2L \theta_{rad})^2 \) of the primary photon beam can be detected.

Let us explain the principle of the proposed method for the case when \( n(\omega) > 1 \) (see insert ‘2’). When the angle \( \theta_{gl} \) increases from 0, TER will be observed, and the reflected photon detector will continue to detect TER photons till \( \theta_{gl} \) becomes greater than \( \theta_{cr}^{TER} \). Measuring at this moment \( \theta_{cr}^{TER} \) and calculating \( \delta \) by the above given formulae one can determine \( n(\omega) \) for \( n(\omega) > 1 \). Similarly, one can determine \( n(\omega) \) for \( n(\omega) < 1 \) replacing the flat reflector by the table shape one shown in the insert “1” of figure 1. The above mentioned dependence of the rate of detection of TER (or TIR) photons on the \( \theta_{gl} \) have the form of the curve 1 and 2 shown in the insert “2” of the figure 1 for ideal and real (with spread, etc) beams, respectively. Roughly \( \Delta \theta_{cr} \) is equal to the error of the measurement of \( \theta_{cr}^{TER} \) (or \( \theta_{cr}^{TIR} \)). In other words, it is necessary to have photon beams with angular spread \( \theta_{acc} \ll \theta_{cr} \), say, \( \theta_{acc} \approx 0.1 \theta_{cr} \).

In the past no such experiments at MeV energies have been carried out, though in many works (see, [9]) it has been proposed, but not realized, to use TER of MeV photons for various purposes, in particular, for monochromatization (filtration) of MeV photon beams. The reason is in the following two requirements. It is necessary to have MeV photon beams 1) with very small angular spread and 2) with sufficient intensities. However, the proposed experiments become realistic recently in connection with the advance of the method of inverse Compton scattering intense photon sources. [10, 11]. Suitable parameters for such experiments are at present available at the facility HiGS of Duke university, which provides \( 10^8–10^{11} \) photons per second in a ~10% BW, Soon it will be available at the ELI facility in Romania, which will provide \( \sim 10^{13} \) MeV photons per second in a ~1% BW. Of course, the intensity of the HiGS beam is much less than the primary photon beam of GAMS5 emitting into \( 4\pi \) solid angle (~10\(^5\)), but it has angular spread of \( \Delta \theta_{rad} \sim 1/\gamma \sim 4 \times 10^{-4} \) rad. As it has been mentioned above the worse monochromaticity is not important for our application.

Let us consider the case when \( n < 1 \). Then assuming that the refractive index of Si is determined by the formula \( n(\omega) = 1 - 0.5(\omega_p / \omega)^2 \), for photons with energy \( \hbar \omega = 2 \) MeV and Si radiator with \( \hbar \omega_p \approx 30 \) eV, one obtains \( \delta (2\text{MeV}) = 2.25 \times 10^{-10} \), and with the help of above formula \( \theta_{cr}^{TER} = 2.25 \times 10^{-5} \) rad. This means that for the measurement of \( n(2\text{MeV}) \) with the help of TER it is necessary to have beam of 2 MeV photons with angular spread, say, \( \theta_{acc} = 2.25 \times 10^{-6} \) rad.

If one uses HiGS photon beam with angular spread \( \Delta \theta_{rad} \sim 1/\gamma \sim 4 \times 10^{-4} \) rad the necessary \( \theta_{acc} = 2.25 \times 10^{-6} \) rad is provided by the fact that only a small fraction equal to \( F = (\theta_{acc} / \theta_{rad})^2 \) of the beam emitted under angles smaller than \( \theta_{acc} = T_0 \gamma / 2L \) strikes the Si reflector. Taking \( T = 3 \) cm, \( L = 10 \) m, one obtains \( \theta_{acc} = 3.36 \times 10^{-8} \) rad, i.e. less than it was required \( \theta_{acc} = 2.25 \times 10^{-6} \) rad. This means that the second requirement is satisfied, and one can carry out the experiment having sufficiently intense photon beam. For such parameters, \( F \approx 10^{-8} \), and the number of TER photons at HiGS will be more than \( N_{TER} = 1 \) per second. With such number of photons and accuracy of the measured \( \theta_{cr}^{TER} \) one can carry out the measurement in short time and determine \( \delta \) at HiGS and show that \( \delta \) is negative or positive. Just in the same manner following the results of [1] and assuming that \( \delta \) is positive one can carry out TIR measurement of \( \delta = 0 \).

Above it has been shown that, in principle, the proposed experiment can be performed. In reality the HiGS beam-line has collimators after which the MeV photon beam has transverse sizes ~3x3 mm\(^2\) in the experimental hall at a distance of about 60 m. One can collimate this beam stronger, especially,
in the vertical direction, down to ~1mm. Using such collimated beam one can make the measurements, detecting with the help of reflected and transmitted photon detectors only the photons, reflected or passing the reflectors. However, some problems remain. Here the method of rotating and fixing the reflectors with microradian accuracy will not be discussed taking into account the nanoradian accuracy achieved in [1] with the help of interferometer. We will not discuss also the problem of the non-planarity and roughness of the reflectors, etc. Nevertheless, it is necessary to consider how the reflected and transmitted photon detectors work, since if $\theta_\mu \approx 10 \mu\text{rad}$ the distance between them will be equal to ~1 cm if the detectors will have distance from the reflector equal to $L_{\text{det}} \approx 1 \text{ km}$.

To overcome this difficulty and to place the reflected and transmitted detectors much closer, say, at distance $L_{\text{det}} \approx (50–100) \text{ m}$, it is proposed to use the set-up shown in figure 2 in which

![Figure 2. The proposed set-up for the reflected and transmitted photon detectors.](image)

the recent progress in positron emission tomography, PET, technology (see [12]) is used. The reflected (transmitted) photon with known energy in the interval $\hbar \omega = 1–10 \text{ MeV}$ produces a Compton electron or $e^-e^+$ pair in the top (bottom) scintillator of the reflected (transmitted) photon detector placed after a distance $L_{\text{det}}$, much shorter than $L_{\text{det}} \approx 1 \text{ km}$, at a few mm from the reflection plane. Since the energy of $e^-$ or $e^+$ is less than $\hbar \omega$ the range of one of them can be up to ~1 cm, and, therefore, due to the escape from the top (bottom) scintillator the energy measured by the top (bottom) photomultiplier, PMT, will be less than the energy $\hbar \omega$ of the reflected (transmitted) photon. It is necessary to use more effective scintillators, say LaBr$_3$, with better characteristics (see [12]). The scintillation light of these charged particles is detected by the top (bottom) PMTs. The transmitted photon detector is placed a little downstream and cannot detect the escaped particles. Such a set up of the detectors allows to detect separately the reflected and passing photons. Let us note that this problem can be solved also with the help of PET liquid xenon time projection chamber (LXeTPC) [13] or proposed LXeTPC on the basis of graphene [14].

3. Conclusions
It is clear that in order to confirm or decline the results of [1] which are very important for experimental and theoretical physics and various applications it is necessary to carry out new measurement better with the help of new methods. As it has been shown above the advance of the inverse Compton scattering photon sources allows at present to measure in relatively simple way $n(\omega)$ of various materials in MeV photon energy region and thus to confirm or decline the very important results of [1]. The proposed method is easier than that of [1] because it can be realized having MeV photon beam with energy spread about 10% and angular orientation microradian accuracy instead of much harder requirements of [1].
References
[1] Habs D, Gunther M M, Jentschel M and Urban W 2012 Phys. Rev. Lett. 108 184802
[2] Doll M et al 2000 J. of Res. of Nat. Inst. of Stand. and Technologies 105 1
[3] Donohue J T 2013 Phys. Rev. Lett. 110 129501
[4] Habs D, Gunther M M, Jentschel M and Thirolf P G 2012 ArXiv:1201.4466
[5] Jentschel M 2013 Gamma Ray Optics, http://www.inn.jir
[6] Habs D 2013 Delbruck scattering and non-perturbative QED and possible applications http://www.eli-np.ro
[7] CERN Courier 2012, July18
[8] Aginian M A, Ispirian K A and Ispiryan M To be published in a) 2013 European Physics Letters; b) 2014 Izvestya of NAS of Armenia; c) 2014 Proc of this Conf.
[9] Kumakhov M A 1986 Radiation of Channeled Particles in Crystals (Moscow Energoatomizdat, in Russian)
[10] Wu Y K 2012 Proc. PAC, TUXB03
[11] Raubenheimer T 2013 Lecture at SLAC Summer School on Electron and Photon Beams
[12] Lewellen T K 2008 Phys. Med. Biol. 53 R287
[13] Aprile E and Doke T 2010 Rev, Mod. Phys. 82 2053
[14] Ispirian K A and Ispiryan R K 2011 Nuovo Cimento 34 37