ISTITUTO NAZIONALE DI FISICA NUCLEARE

Sezione di Trieste

INFN/AE-91/02

22 febbraio 1991

G. Cantatore, L. Dabrowski, F. Della Valle, E. Milotti and C. Rizzo

PROPOSED MEASUREMENT OF THE VACUUM BIREFRINGENCE INDUCED BY A MAGNETIC FIELD ON HIGH ENERGY PHOTONS

Servizio Documentazione
dei Laboratori Nazionali di Frascati

PROPOSED MEASUREMENT OF THE VACUUM BIREFRINGENCE INDUCED BY A MAGNETIC FIELD ON HIGH ENERGY PHOTONS

G. Cantatore, F. Della Valle, E. Milotti

Dipartimento di Fisica, Universita' di Trieste,
Via A. Valerio 2, 34127 Trieste, Italy

and

L. Dabrowski, C. Rizzo

INFN, Sezione di Trieste, Via A. Valerio 2, 34127 Trieste, Italy

Abstract : We propose an experimental set-up to observe and measure the interaction between high energy photons and a strong magnetic field. The successful measurement of such an effect would amount to a direct observation of QED vacuum polarization.

(Submitted to Physics Letters B)

One of the few nonperturbative results of Quantum Electrodynamics is the effective Euler-Heisenberg-Weisskopf (EHW) lagrangian [1]. Because of the universality of electromagnetic interactions, it describes the interaction between photons as well as between photons and external field, and introduces nonlinear corrections to field equations. By using the exact solutions of the Dirac equation in an almost constant external field it is possible to incorporate the vacuum polarization due to electron pairs to all orders in the external field (neglecting only the radiative corrections due to virtual photons).

Important confirmations of the nonlinear effects in Quantum Electrodynamics come from the experiments on Delbruck scattering [2], g-2 experiment [3], and the muonic atom spectroscopy [4]. As far as the Delbruck scattering is concerned there is experimental evidence only for the imaginary part of the scattering amplitude and for energies above the pair production threshold, and in the last two decades no significant progress has been reported. There, as also in the g-2 experiment and in the muonic atom spectroscopy, the QED vacuum polarization graph is one of several contributions to the measured effect.

In this letter we propose another experimental set-up to probe the nonlinearity of the EHW lagrangian by measuring the vacuum birefringence induced by a strong magnetic field. The lowest order graph which enters the EHW lagrangian is shown in figure 1a; thus, our proposal can be also regarded as a direct measurement of the vacuum polarization in QED.

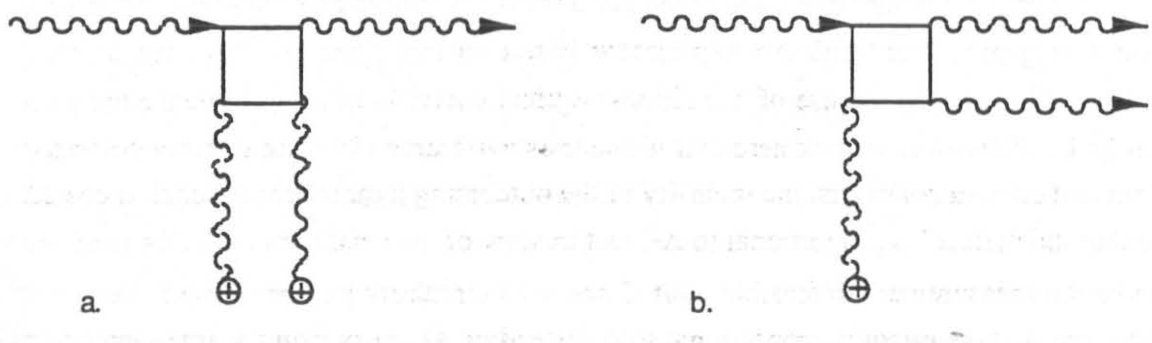

Figure 1: a. The lowest order Feynman diagram contributing to light-field scattering. b. Another possible contribution of the same order is the photon-splitting diagram. Since in our setup we may only detect collinear photons, a theorem by Adler et al. applies [14] and the photon-splitting diagram vanishes; in any case this effect is small and we can safely neglect it (cfr. [5] and [16]).

wider energy range. Since we use higher energy photons, with respect to [6] we can improve the sensitivity by few orders of magnitude.

As a source of high energy polarized photons we propose to use the Compton scattering of a polarized laser beam on a high energy electron beam in a circular machine. The possible polarization analysers at high energies are the oriented crystals. The absorption rates for the high energy photons depend on the orientation of the polarization axis with respect to the crystal symmetry axes [8] due to the interference effects observed in the high energy production of the electron pairs. The effect grows with the depth of the crystal, while absorption causes an exponential decrease in the number of photons; later we shall argue on the basis of the available crystal data that the method is feasible in our case, and that there is an optimal crystal length for a given electron energy.

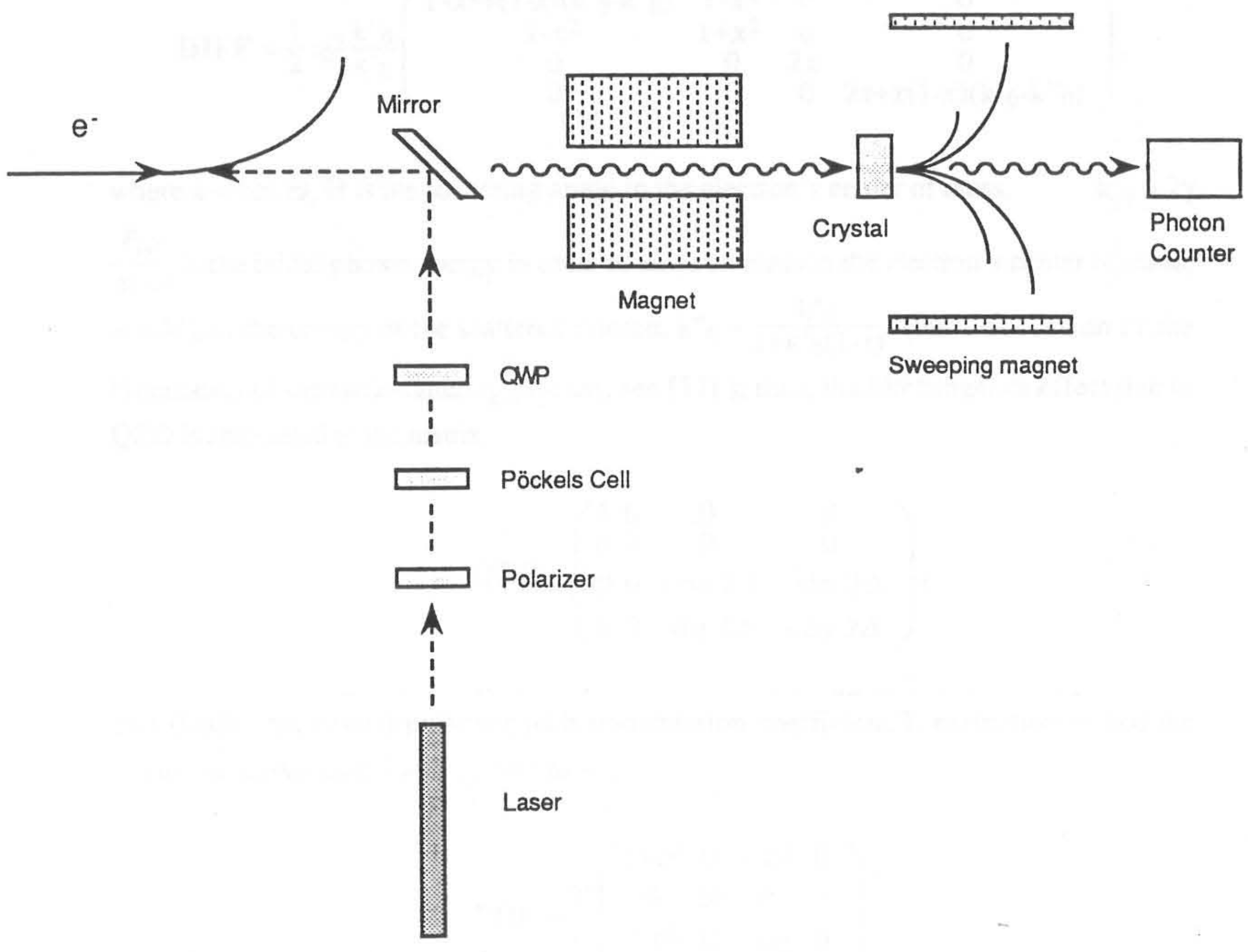

Figure 2: Layout of the proposed experimental apparatus. A Pöckels cell is also included: it allows to switch electrically between opposite circular polarization states.

The layout of the apparatus is shown in figure 2: a continuous-wave laser beam is linearly polarized and then crosses a quarter-wave plate so that it becomes circularly

$$D = \int_{-1}^{x_{max}} \left(\frac{k''_0}{k'_0}\right)^2 [\, 2x + x\,(1-x)\,(k'_0 - k''_0)\,]\, dx \qquad (8)$$

Next,we choose the threshold for the scattered photon energy as half the maximal energy, this corresponds to $x_{max} = \frac{k_0'}{(1+k_0')}$ and to most backscattered photons since the cross-section for Compton scattering is strongly forward-peaked in the laboratory system: the values of A and D can then be computed by numerical integration (figure 4).

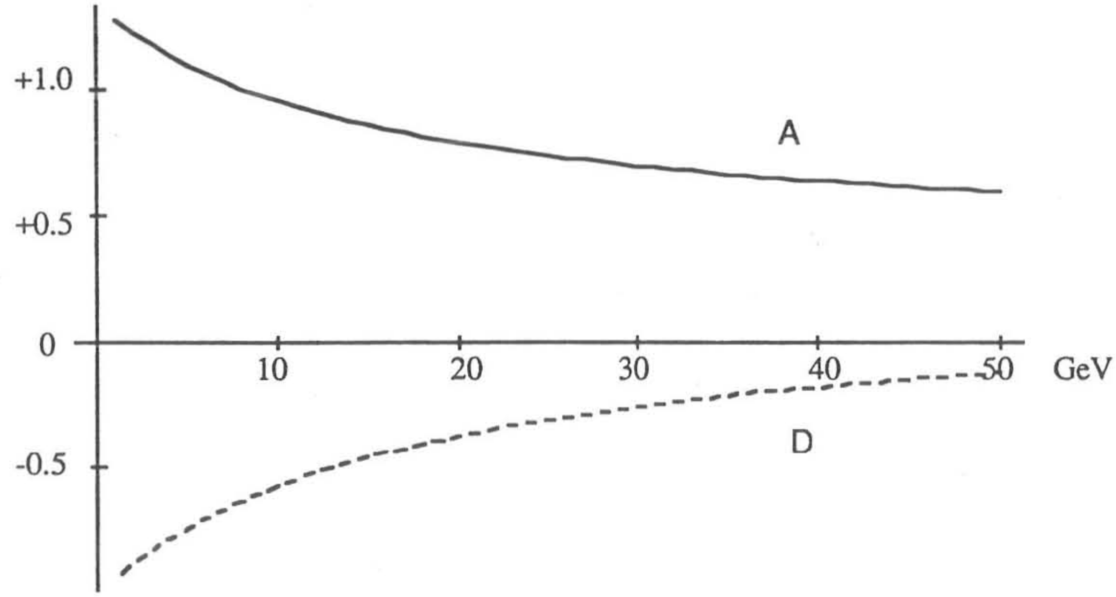

Figure 4: The coefficients A (solid curve) and D (dashed curve) obtained by numerical integration (see text) vs. the electron energy, for a red laser ($\hbar\omega \approx 2.5$ eV).

Formula (6) is the required result: it is a linear function of Δ, and shows that it can be found by counting the number of backscattered photons with the magnetic field turned on and then off, and with left and right circular polarizations.

As we remarked earlier, the available polarizers become more effective for large crystal thickness, but they also absorb more photons: eventually both effects are accounted for in formula (6). Now notice that the number of detected photons per unit time is proportional to $T\,A\,(1+\varepsilon^2)$, while in order to have $\frac{\text{signal}}{\text{noise}} \approx 1$ one needs

$$N_{TOT} \sim \left\{ 2\Delta \, \frac{D\,(1-\varepsilon^2)}{A\,(1+\varepsilon^2)} \right\}^{-2} \qquad (9)$$

Table: Machine parameters

Energy	26 GeV
Current	$3.6 \cdot 10^{17}$ electrons/sec
Length of straight sections	10 m

We also assumed a continuous-wave laser beam, with a power of 1 Watt, with a beam diameter of 0.5 cm, and $\hbar\omega = 2.5$ eV; as before, we assumed a high field magnet ($B_0 = 10$ Tesla, $L = 10$m).

With these parameters, and with no background, it turns out that the maximum photon energy is about 13 GeV, the average photon energy is about 10 GeV; moreover, it takes roughly 10^7 photons to observe the effect, and 5 10^3 photons/sec are produced, so that we expect ~ 2000 seconds to make a complete measurement.

We estimated the background due to interactions between beam and residual gas in the pipe from the measurements in [13]: the background photons approximately double the total counts, therefore the measurement time is multiplied approximately by 4.

We wish to remark that most of the experimental apparatus proposed in this Letter already exists, for instance Compton backscattering of circularly polarized photons is used to detect the longitudinal electron polarization in large electron machines [14].

Acknowledgements: We are indebted to Prof. E. Zavattini for suggesting the problem, several discussions and the encouragement, and to Prof. G. Barbiellini for helpful suggestions.