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INTERFERENCE EXPERIMENT AND PHOTON STATISTICS FOR SYNCHROTRON RADIATION FROM ELECTRONS IN A STORAGE RING

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An interference experiment with synchrotron-radiation photons from relativistic electrons in a storage ring has been carried out. It was shown that this radiation produces an interference pattern in a Jamin interferometer which remains unaltered as the radiation intensity is reduced to a level corresponding to a few electrons in the orbit. At this low intensity the synchrotron radiation consists of statistically independent photons. This is confirmed by an analysis of the quantum state of the radiation field due to an electron in the storage ring, and by preliminary measurements of the distribution function for the number of pulses from an image converter.

1. INTRODUCTION

THERE has recently been renewed interest in the interference properties of individual photons. In particular, Dontsov and Baz'[1] have noted that the results of previous interference experiments[2-4] have not been sufficiently reliable, since the individual photons were not detected directly and, consequently, there was no guarantee that they were statistically independent. Dontsov and Baz' therefore performed an interference experiment in which the individual photons were recorded[1]. They showed that, under their experimental conditions, in which they used monochromatic light of low intensity, so that the corresponding photons were statistically independent, there was no interference.

Since the result of this experiment is inconsistent with existing ideas, we have decided to repeat it under different conditions. We note that after the publication of[1], Sanin et al.[5] demonstrated experimentally the diffraction of X-ray photons by a crystal lattice. This result cannot, however, be regarded as a refutation of the report given in[1] because, in our view, this type of experiment involves the separation of the interfering rays to macroscopic distances.

One of the main experimental difficulties encountered in interference experiments of this kind is the choice of the source of statistically independent photons. In our view, one of the most suitable types of radiation for this purpose is the synchrotron radiation from one or a few relativistic electrons in a storage ring. We therefore selected the 70 MeV electron storage ring at the Physicotechnical Institute of the Ukrainian Academy of Sciences,[6] as the source of radiation for our interference experiment. This paper presents a report on this experiment.

2. EXPERIMENTAL METHOD

The interference experiment is illustrated schematically in Fig. 1. The storage ring[6] which is used as the source of synchrotron radiation is a racetrack system with four straight gaps of 2×50 cm and 2×80 cm. The radius of the equilibrium orbit is 50 cm. The magnetic field index is 0.27, and the orbital electron frequency is 52.28 MHz. The measurements were carried out with a beam life-time in the storage ring of 180 sec and electron energy of 70 MeV. At this energy a single electron radiates at the rate of 2.5×10^8 eV/sec, and about 12% of the corresponding synchrotron-radiation photons lie in the range between 3000 and 6000 Å.

The radiation leaves the storage ring through the transparent window 2 (Fig. 1) whose plane is perpendicular to the tangent to the equilibrium orbit and is at a distance of 50 cm from it. The size of the window is 5×2 cm. Thus, with the particular transverse size of the electron bunch and divergence of the synchrotron radiation, the size of the light source was 4.5×0.5 mm and the maximum divergence of the radiation was 4.5×10^{-2} rad. The radiation was directed on to the interferometer by an optical system consisting of two flat mirrors 3, 5 and two thin lenses 4, 6 (see Fig. 1) whose optical power was, respectively, +0.5 and +0.75 diopters. Under these conditions the interferometer received a slightly divergent beam of light. The light transmission of the optical system which was determined experimentally was found to be 0.08.

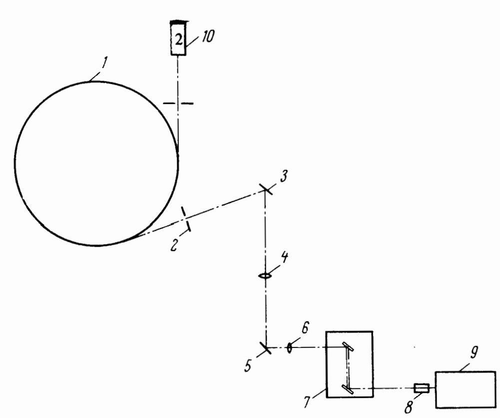

FIG. 1. Schematic illustration of the interference experiment. 1—storage ring, 2—glass flange for extracting the light beam from the storage-ring chamber, 3, 5—plane mirrors, 4, 6—lenses, 7—Jamin interferometer, 8—objective, 9—image converter, 10—system for measuring the number of electrons.

The interference pattern was produced with a Jamin interferometer in which the principal maximum corresponds to zero path difference. This fact is of particular importance because synchrotron radiation has a broad spectrum. The interferometer mirror thickness is 10 mm so that the interfering rays are separated by 6 mm. The distance between the mirrors is 25 cm. Special measures were taken in the adjustment of the interferometer to eliminate parasitic rays due to multiple reflection inside the mirrors. As a result of losses by scattering, multiple reflection, and absorption, the light transmission of the interferometer is 0.01. It follows that the effective fraction of the light flux leaving the storage-ring chamber and used in the experiments was 10^{-3}.

The interferometer was adjusted at high intensities, using a viewing tube, and thereafter the interference pattern was recorded with an image converter operating under continuous conditions. The photocathode of the converter had a sensitivity maximum near the maximum of the synchrotron radiation. The geometric resolving power was 7 line pairs/mm on the first photocathode.

To reduce the natural noise level the first photocathode was cooled with liquid nitrogen vapor. A substantial reduction in the thermionic component of the noise was observed when the temperature in the chamber adjacent to the photocathode was reduced to $-100°C$.

The residual noise at the exit screen was 0.2 pulses/sec-mm^2. This produced 1.5 pulses/sec on the area occupied by the image of the interference pattern. The flashes were photographed on a film with a sensitivity of 2000 units. We note that the residual noise from the cooled cathode was very dependent on the voltage applied to it. To reduce the residual noise we reduced the voltage on the first photocathode, and this lead to an increase in the contribution of the background due to the subsequent converter stages. This contribution was however substantially reduced by negative duplication.

The stable operation of the entire optical system was checked by projecting the interference pattern due to a hot-filament lamp onto the converter cathode.

The number of electrons circulating in the orbit was determined by measuring the synchrotron radiation with an FÉU-36 photomultiplier operating in the integrating mode. The photomultiplier gain was chosen so that the "steps" corresponding to the discontinuous change in the intensity due to the loss of a single electron could easily be distinguished (Fig. 2).

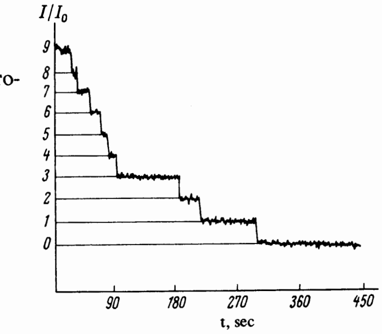

FIG. 2. Intensity of synchrotron radiation as a function of time. The zero on the vertical axis corresponds to the photomultiplier noise level. I_0 is the intensity of synchrotron radiation from a single electron.

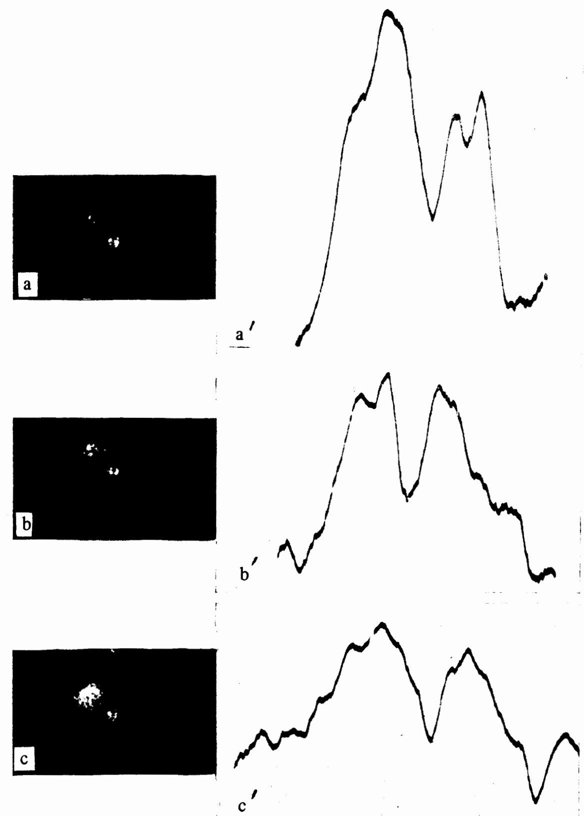

FIG. 3. Results of interference experiments: a, b, c—interference patterns for 50, 25, and 10 electrons in orbit respectively, a', b', c'—photometric traces corresponding to interference patterns due to 50, 25, and 10 electrons in orbit. The spot on the left and above the interference pattern represents noise which was distributed in a very nonuniform fashion over the converter screen. The working zone was of course chosen in the region of low noise.

3. EXPERIMENTAL RESULTS

Two series of photographs of the interference patterns were taken from the converter screen. In the first series of photographs the interference patterns were recorded with different light intensities in order to establish the presence of interference. The density of the negatives was kept the same by changing the exposure and duplication was not employed. In the second series of photographs we used a standard exposure of 2 ± 2 ± 0.15 sec with 15 or fewer electrons in orbit. These photographs were taken to obtain data on the light-beam intensity and the statistics of the radiated photons.

The results of the interference experiments are shown in Fig. 3. The zero-order maximum, the first minimum, and the first maximum of the interference pattern formed by the Jamin interferometer were projected onto the converter cathode. The image diameter on the converter screen was 3.3 mm. It is clear from Fig. 3 that an interference pattern is formed at relatively high intensities and persists as the intensity is reduced down to a level corresponding to 10 radiating electrons. However, the detection of the interference pattern becomes increasingly difficult as the intensity is reduced, owing to the increasing contribution of the natural noise of the image converter (Fig. 3c, c′). Nevertheless, there is no doubt that interference does take place at light intensities corresponding to 5 or more electrons in orbit.

Similar results are obtained when the Jamin interferometer is replaced by a Fresnel biprism.

Analysis of the results obtained for the second series of photographs (altogether 22 negatives) showed that the mean number of photoelectrons from the converter cathode for 10 electrons in orbit corresponded to 6.5 pulses/sec. After subtracting the noise level corresponding to 1.5 pulses/sec we obtained a useful signal of 5 pulses/sec.

If we assume that the quantum yield of the photocathode is 0.1, we find that the photon flux corresponding to 5 electrons in orbit is 25 photons/sec. Since the light transmission factor of the interferometer is 0.01, the photon flux at the entrance to the interferometer is 2500 photons/sec. Consequently, the mean distance between the photons is 10^5 m, which is much greater than the linear dimensions of the interferometer. For a Poisson distribution, this practically excludes the simultaneous appearance of two photons in the interferometer.

On the other hand, analysis of the second series of photographs shows that the mean and the variance of the number of photoelectrons are equal to within statistical error, i.e., the photons are distributed in accordance with the Poisson law. However, the accuracy of this result is low, and it must be regarded as preliminary because we have analyzed only a small number of photographs (16 with useful signal and 6 purely noise photographs). Nevertheless, the conclusion that the photons were statistically independent may be regarded as correct because it also follows from the theoretical analysis given below.

4. STATISTICS OF SYNCHROTRON RADIATION PHOTONS

The energy of the synchrotron-radiation photons is usually negligible in comparison with the energy of the radiating electrons and, therefore, when the parameters of the synchrotron radiation are calculated we can probably neglect the electron recoils on emission. This is confirmed by the fact that classical electrodynamics[7] gives correct predictions for all the parameters of the synchrotron radiation. We note that this is not so in the case of the motion of the electrons themselves, which is substantially influenced by quantum fluctuations in the radiation[8].

It may therefore be expected that no substantial errors are introduced by neglecting the recoils in the analysis of the quantum state of the radiation field. On the other hand, this analysis provides additional information as compared with the classical theory[7] and the usual quantum-mechanical analysis[9] because the problem of radiation by a classical current without recoil can be solved exactly without the use of perturbation theory.

Glauber[10] has shown that, in this case, the radiation field is in the so-called coherent state:

$$\left|\alpha\right\rangle=\prod_l e^{-\frac{1}{2}|\alpha_l|^2}\sum_{n_l=0}^{\infty}\frac{\alpha_l^{n_l}}{(n_l!)^{1/2}}\left|n_l\right\rangle, \qquad (1)$$

where $|n_l\rangle$ is the vector of the n-th quantum state of the l-th mode of the electromagnetic field. The coherent state is completely characterized by a set of complex amplitudes α_l which in the case of a classical radiating current of density $\mathbf{j}(\mathbf{r}, t)$ are given by the following formula[10]:

$$\alpha_l(t)=i\left(\frac{2\pi}{\hbar\omega_l}\right)^{1/2}L^{-3/2}\int_0^t dt\int d\mathbf{r}\,\mathbf{j}(\mathbf{r},t)\,\boldsymbol{\varepsilon}_l^*e^{-i(\mathbf{k}_l\mathbf{r}-\omega_l t)}. \qquad (2)$$

In this expression ϵ_l is the polarization vector, $\mathbf{k}_l$, ω_l is the wave vector and the radiation frequency respectively, and L^3 is the normalizing volume.

For an electron moving in a circular orbit of radius R with frequency ω we have

$$\mathbf{j}(\mathbf{r},t)=ev\delta(\mathbf{r}-\mathbf{r}_0(t)),\ r_{0x}=R\cos\omega t,\ r_{0y}=R\sin\omega t,\ r_{0z}=0. \qquad (3)$$

Substituting (3) in (2), and evaluating the integral, we obtain

$$\alpha_l(t)=\frac{\sqrt{\pi}ev\varepsilon_\perp^*}{(2\hbar\omega_l)^{1/2}L^{3/2}}\sum_{p=-\infty}^{\infty}e^{i(\frac{1}{2}\pi(p-1)-p\varphi_l)}\frac{e^{i(p\omega+\omega_l)t}-1}{p\omega+\omega_l}$$
$$\times\left(J_{p-1}(Rk_\perp)e^{i(\varphi_l+\Delta_l)}-J_{p+1}(Rk_\perp)e^{-i(\varphi_l+\Delta_l)}\right), \qquad (4)$$

where $k_\perp$ and $\epsilon_\perp$ are the projections of the wave vector and the polarization vector on the plan of the orbit, respectively, $\Delta_l = \tan^{-1}(\epsilon_x^*/\epsilon_y^*)$, $\varphi_l = \tan^{-1}(k_y/k_x)$, and J_{p-1}, J_{p+1} are the Bessel functions.

It follows from Eq. (4) that, for sufficiently large t, the radiation is largely concentrated near frequencies which are multiples of the orbital frequency: $\omega_l \approx p\omega$. Let us now determine the number of photons emitted near each of these lines. By summing the quantities $|\alpha_l|^2$ which represent the mean number of photons, we obtain the following expression for the mean number of photons emitted near the p-th line per unit solid angle:

$$n_p=\frac{e^2\beta^2p\omega}{8\pi c\hbar}t\,(J_{p-1}(k_\perp R)\,(|\varepsilon_x|^2+|\varepsilon_y|^2-2\operatorname{Im}\varepsilon_x^*\varepsilon_y)$$
$$+J_{p+1}^2(k_\perp R)\,(|\varepsilon_x|^2+|\varepsilon_y|^2+2\operatorname{Im}\varepsilon_x^*\varepsilon_y)$$
$$+2J_{p-1}(k_\perp R)J_{p+1}(k_\perp R)\,((|\varepsilon_x|^2-|\varepsilon_y|^2)\cos 2\varphi_p+2\operatorname{Re}\varepsilon_x^*\varepsilon_y\sin 2\varphi_p) \qquad (5)$$

As expected, the number of radiated photons is proportional to time.

Equation (5) can be used to obtain the following expression for the power radiated per unit solid angle:

$$W_p=\frac{ce^2\beta^2p^2}{2\pi R^2}\left|\beta J_p'(\beta p\sin\theta)\,\varepsilon_1-iJ_p(\beta p\sin\theta)\operatorname{ctg}\theta\,\varepsilon_2\right|^2, \qquad (6)$$

where θ is the polar angle, $\beta = v/c$, ϵ_1 and ϵ_2 are the components of the polarization vector, and the differentiation of the Bessel functions is carried out with respect to the complete argument.

Equation (6) is similar to the Schott formula and, therefore, the radiated power, the spectrum, the angular distribution, and the polarization of the radiation are described by the same formulas as in classical electrodynamics.

On the other hand, it follows from Eq. (1) that the number of radiated photons is distributed in accordance with Poisson's formula, i.e., the photons are distributed in time in a statistically independent fashion. The same conclusion is obtained by calculating the number of counts recorded by a photon counter. It was shown in[10] that the number of counts recorded with a counter in a beam of coherent radiation is also distributed in accordance with Poisson's law, and there is no correlation between the counts recorded by two counters.

5. CONCLUSIONS

The results of the present research lead to the following conclusions:

1. The synchrotron-radiation photons emitted by five or more electrons in the storage ring form an interference pattern in the Jamin interferometer (and also in the Fresnel biprism system).

2. Theoretical analysis and preliminary measurements have shown that, at such intensities, the synchrotron-radiation photons are distributed in a statistically independent fashion.

The mean photon flux in this experiment was 2500 photons per second. With such intensities and a Poisson photon distribution the simultaneous appearance of two photons in the interferometer is practically impossible.

The above results are in agreement with theory but are inconsistent with the results reported by Dontsov and Baz'[1].

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