Synchronization of photons due to interference of intensities

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(Submitted 23 October 1979)
Pis'ma Zh. Eksp. Teor. Fiz. **31**, No. 2, 84–88 (20 January 1980)

The existence of a new optical effect, which occurs in strong and correlated energy fluctuations of the light pulse subjected to a narrow-band filtration, is predicted. This effect may be used to determine the duration and statistics of short-pulse photons and also to measure the decay times of short-lived states without using high-speed photodetectors.

PACS numbers: 42.10.Jd, 42.65.Gv

Synchronization of photons due to interference of intensities (SPII) occurs when a light pulse of duration τ_p and large spectral width $\Gamma_i \gg \tau_p^{-1}$ begins to fluctuate strongly in the integral energy after passing through the spectral filter with a pass band $\gamma \ll \tau_p^{-1}$. If there are two such closely spaced filters (within the limits of the area of coherence) (see Fig. 1), then the number of photons per pulse (n_1 and n_2, respectively) passing through them fluctuates in a correlated way, so that the correlation factor $g^2 = (\langle n_1 n_2\rangle - \langle n_1\rangle \langle n_2\rangle)/\langle n_1\rangle \langle n_2\rangle$ is of the order of unity. Such fluctuations can be recorded by inertial photodetectors with a reaction time $\tau_d \gg \tau_p$. The correlation decreases with increasing γ: $g^{(2)} \sim (\gamma\tau_p)^{-1}$. The $g^{(2)}(\gamma)$ dependence allows to determine the duration of the pulse. If the recorded pulse is produced as a result of de-excitation of a certain state, then the decay time τ of this state is defined.

The correlated fluctuations (interference) of the instantaneous intensities of light were observed by Brown and Twiss [1] in an experiment whose geometry coincides with that in Fig. 1. Their experiment, however, required high-speed detectors, because otherwise the observed correlation would be small $g^{(2)} \sim (\tau_d \Gamma_i)^{-1}$, where Γ_i is the spectrum width of the recorded light (see also Ref. 2). Only Γ_i can be determined from the spectral parameters [2,3] by using the method of Brown and Twiss. [1] These results, which depend on the steady light in Ref. 1, are closely associated with the general characteristics of measurement of the interference. [4]

A quantum description of the interference of the intensities of light involves the interference of two-photon amplitudes: the direct amplitude and the amplitude corresponding to permutation of the photons between the detectors D_1 and D_2. Only the amplitudes of the indiscernible photons interfere. The photons, which overlap within the limits of their coherence length $\tau_c \sim \Gamma_i^{-1}$ (Fig. 2a), are indistinguishable at small-angle recording; the number of such events is $\sim \tau_d/\tau_c$. The other two-photon events (Fig. 2b) are background events whose number is $\sim (\tau_d/\tau_c)^2$, which gives an estimate of $g^2 \sim \tau_c/\tau_d \ll 1$.

The SPII can be easily understood from the above explanation: if the light is pulsed and its coherence length is increased to $\tau_c \sim \gamma^{-1} \ll \tau_p$ with the help of a filter,

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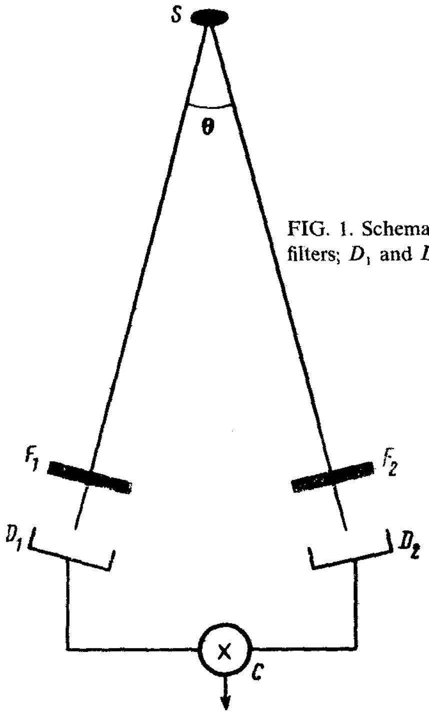

FIG. 1. Schematic of the experiment: S, light sources; F_1 and F_2, spectral filters; D_1 and D_2, photodetectors; C, correletor.

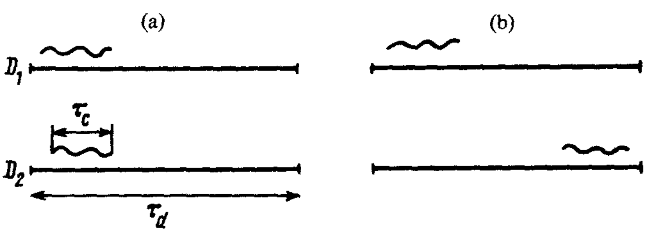

FIG. 2. Time diagram of photorecording: (a) photons recorded by detectors D_1 and D_2 are indistinguishable and there is an interference; (b) background event: photons are distinguishable and there is no interference.

then all the photons of a given pulse, which have passed through the filter, are synchronous, i.e., they overlap at the coherence length and hence are indistinguishable. Thus, the interference is maximum and $g^{(2)} \sim 1$ independent of τ_d.

The SPII can also be easily understood in the classical limit. For simplicity, let us examine the light with Gaussian statistics. As is well known, [2] its instantaneous intensity fluctuates strongly with a characteristic period τ_c. For the original light $\tau_c \sim \Gamma_i^{-1} \ll \tau_p$ (Fig. 3a), so that the detector determines the total energy of the pulse with the relative error $(\Gamma_i \tau_p)^{-1/2}$, which gives $g^{(2)} \sim (\Gamma_i \tau_p)^{-1} \ll 1$.The statistics do not change after filtration, but τ_c increases and becomes comparable with τ_p (Fig. 3b). This means that the total energy of the pulse fluctuates. The estimate of g^2 has the form: $g^{(2)} \sim \gamma^{-1} \min(\gamma_p^{-1}, \gamma)$.

In the quantitative description of SPII, we limit ourselves to Gaussian light,

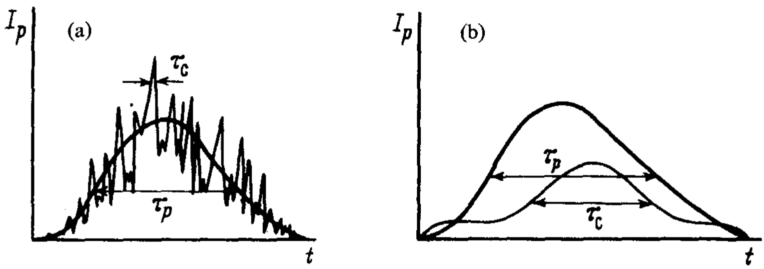

FIG. 3. Pulse shape [(a) before filtration; (b) after filtration]. The heavy line represents average intensity and the fine line denotes instantaneous intensity.

which, in combination with the condition $\tau_d \gg \tau_p$, allows us to express $g^{(2)}$ in terms of the Green's function of the field in the frequency representation $G(\omega_1,\omega_2)$:

$$g^{(2)} = \int d\omega_1 d\omega_2 \chi_1(\omega_1)\chi_2(\omega_2)|G(\omega_1,\omega_2)|^2 / \int d\omega \chi_1(\omega) G(\omega,\omega) \times \int d\omega \chi_2(\omega) G(\omega,\omega), \qquad (1)$$

where $\chi_1(\omega)$ and $\chi_2(\omega)$ are transparencies of the filters having the shape of narrow peaks with half-widths γ_1 and γ_2 and centers at certain frequencies ω_1^f and ω_2^f; moreover, the frequency difference $\omega_{12}^f = \omega_1^f - \omega_2^f$ is small compared with Γ_i. For simplicity, in describing the spectrum of light we shall use the model for inhomogeneously broadened line with the contour $F(\omega)$ having the width $\Gamma_i \gg \tau_p^{-1}$. Dropping the multiplier, which describes the unessential spatial dependence G for small-angle recording, we obtain for the time dependence:

$$G(t_1,t_2) = \int_{-\infty}^{\infty} d\omega\, F(\omega)[I_p(t_1) I_p(t_2)]^{1/2} e^{i\omega(t_1 - t_2)}, \qquad (2)$$

where $I_p(t)$ is the intensity of the light pulse with respect to time. For the G components, which give the main contribution to Eq. (1), we can easily obtain from Eq. (2) the approximate expression:

$$G(\omega_1,\omega_2) = 2\pi F(\omega^f) I_p(\omega_2 - \omega_1), \qquad (3)$$

where $I_p(\omega)$ is the Fourier transform of the $I_p(t)$ function. We can see that the $F(\omega^f)$ factor drops out from the expression (1) for $g^{(2)}$. Therefore, the SPII is a spectroscopic effect free from nonuniform broadening.

The maximum SPII occurs at $\gamma_{12} \ll \tau_p^{-1}$, where $\gamma_{12} = \gamma_1 + \gamma_2$. Thus, it follows from Eqs. (1) and (3) that $g^{(2)}$ is a time form factor of the light pulse:

$$g^2 = |I_p(\omega_{12}^f)|^2 / I_p^2(\omega = 0), \qquad (4)$$

here $g^{(2)} = 1$ at $\omega_{12}^f = 0$. If the experimental dependence $g^{(2)}(\omega_{12}^f)$ is known, then we can determine not only τ_p but can also reconstruct the complete shape of $I_p(t)$ with some additional information. At $\gamma_{12}\tau_p \gg 1$, the asymptotic form $g^{(2)} \sim (\gamma_{12}\tau_p)^{-1}$ indicated above follows from Eqs. (1) and (3). The $g^{(2)}(\gamma)$ dependence makes it possible to determine τ_p, if the shape of the pulse is known.

Apparently, the SPII, which is sensitive only to amplitude modulation of the pulses, makes it possible to determine the fraction κ of such modulation in the pulses of arbitrary statistics. To solve the problem of determining $I_p(t)$ without reference to satistics of the pulses, it is sufficient for them to excite spontaneous fluorescence with the de-excitation time $\tau \ll \tau_p$. Thus, the statistics of the fluorescence pulses are Gaussian ($\kappa = 1$) and the shape reproduces $I_p(t)$.

The SPII makes it possible to investigate the kinetics of decay of the short-lived states. To do this, it is necessary to excite such a state by an action, which is instantaneous in the scale of its lifetime, for example, by a supershort laser pulse, and to observe the fluorescence light accompanying the decay. In particular, for exponential kinetics $I_p(t) \sim e^{-t/\tau}\theta(t)$ it follows from Eqs. (1) and (3) [compare with Eq. (4)] that:

$$g^{(2)} = \Gamma(\Gamma + \frac{1}{2}\gamma_{12})\left[(\omega_{12}^f)^2 + \left(\Gamma + \frac{1}{2}\gamma_{12}\right)^2\right]^{-1}, \qquad (5)$$

where $\Gamma = \tau^{-1}$ is the natural width of the fluorescence line. By comparing Eq. (5) with the experimental dependence $g^{(2)}(\omega_{12}^f, \gamma_{12})$, we can verify the exponential dependence of the kinetics of decay of the state and determine its lifetime τ. Thus, we can determine with the help of SPII the natural line width against the background of large inhomogeneous broadening.

We shall briefly compare our approach with the gating method, which allows a direct measurement of the shape of the short pulses and of the lifetimes of the short-lived states without using the high-speed photodetectors (image converters). In the gating method we use light-controlled shutters, which work on the principle of illuminating the dyes, or the Kerr effect, which is produced by a part of the energy of the exciting pulse. The main deficiency of the gating method is its ineffectiveness outside the region of gating, for example, in the far ultraviolet (UV) or the infrared range, and also in the case of low-power exciting pulses. The proposed method, which does not have these disadvantages, can be used anywhere there are suitable spectral instruments, for example, diffraction grating in the UV region.

Synchrotron radiation from storage rings is a sequence of short (subnanosecond) pulses.[5] Using it, we can observe the SPII both in the optical and in the nuclear transitions, where the narrow-band recording with variable detuning can be achieved with the help of Mössbauer effect.

The author thanks S. G. Rautian for useful discussions and support, A. V. Gaĭner, G. I. Surdutovich, and A. M. Shalagin for a discussion of the results, and A. N. Skrinskiĭ for stimulating an interest in synchrotron radiation.

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