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Biphoton Light Generation in Polarization-Frequency Bell States

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Abstract—Four polarization-frequency Bell states are obtained experimentally for photon pairs (biphotons) emitted during spontaneous parametric scattering from continuous pumping in the collinear frequency-nondegenerate regime. The polarization properties of such states are investigated. It is shown that biphoton light in the singlet Bell state is not polarized in the second as well as fourth order in the field. *© 2002 MAIK "Nauka/Interperiodica".*

1. BELL STATES

Entangled states of quantum systems occupy a significant place in quantum optics and especially in quantum informatics. The concept of entanglement of quantum system was proposed for the first time by Schrödinger (in connection with the well-known Einstein–Podolsky–Rosen paradox) in [1]; however, this property was not defined exactly in that publication. After some time, entangled states ceased to be the object of just philosophical discussions and gedanken experiments since various methods of their experimental preparation had been developed. Accordingly, more rigorous definitions of such states were proposed. If we confine ourselves to the case of a pure state of a complete quantum-mechanical system consisting of several parts, the property of entanglement is defined as nonfactorizability of the overall wave function and can be reduced to the existence of quantum correlations between the parts of the system [2]. Among pure entangled states of two-quantum systems, the so-called Bell states [3],

$$\begin{aligned} \Phi^{\pm} &\equiv \frac{1}{\sqrt{2}}(|\uparrow\uparrow\rangle + |\downarrow\downarrow\rangle), \\ \Phi^{\pm} &\equiv \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\uparrow\downarrow\rangle), \end{aligned} \tag{1}$$

play a special role. Here, we assume that each quantum system has two eigenstates $|\uparrow\rangle$ and $|\downarrow\rangle$ (this may be a particle with a spin of 1/2, an atom in a resonant field, a polarized photon, etc.) It is these states that are used for verifying Bell inequalities, in experiments on quantum teleportation, in a number of protocols of quantum cryptography, and other trends in quantum optics. In particular, such states form a convenient basis for describing an arbitrary quantum state of two two-level systems. The state Ψ^- is often referred to as a singlet state since it is similar to the antisymmetric state of two particles with a spin of 1/2.

2. GENERATION OF BELL STATES OF PHOTONS DURING SPONTANEOUS PARAMETRIC SCATTERING

Entangled states have been realized experimentally for various quantum systems such as two atoms, an atom and a photon, and two ions. The experiments with entangled (correlated) states of photons have become the most popular. The most effective method for generating correlated photon pairs is that involving spontaneous parametric scattering (SPS) [4].

In the case of spontaneous parametric scattering, the pumping radiation with frequency ω_p and wave vector $\mathbf{k}_p$ incident on a crystal with a quadratic nonlinearity of χ leads to the emergence of scattered radiation at the crystal exit; the state of the latter radiation can be presented in the form

$$|\Psi\rangle = |\text{vac}\rangle + \frac{1}{2}\sum_{\mathbf{k},\mathbf{k}'} F_{\mathbf{k}\mathbf{k}'}|1_{\mathbf{k}}, 1_{\mathbf{k}'}\rangle, \tag{2}$$

where $|\text{vac}\rangle$ stands for the vacuum state and $|1_{\mathbf{k}}, 1_{\mathbf{k}'}\rangle$ is the state with one photon in mode $\mathbf{k}$ (signal photon) and one photon in mode $\mathbf{k}'$ (idler photon), which is often referred to as a biphoton. Indices $\mathbf{k}$ and $\mathbf{k}'$ label the frequency, spatial, and polarization modes. The quantity $F_{\mathbf{k}\mathbf{k}'}$ is often called the biphoton amplitude. In the stationary case, when radiation emitted by a CW single-mode laser is used for pumping and the medium parameters do not depend on time, the biphoton amplitude is proportional to $\delta(\omega + \omega' - \omega_p)$, where ω and ω' are the frequencies of the signal and idler photons. If, in addition, the scattering occurs in a plane layer unbounded in the directions transverse to the wave vector of pumping, $F_{\mathbf{k}\mathbf{k}'}$ is also proportional to $\delta(\mathbf{k}_\perp + \mathbf{k}'_\perp)$, where $\mathbf{k}_\perp$ and

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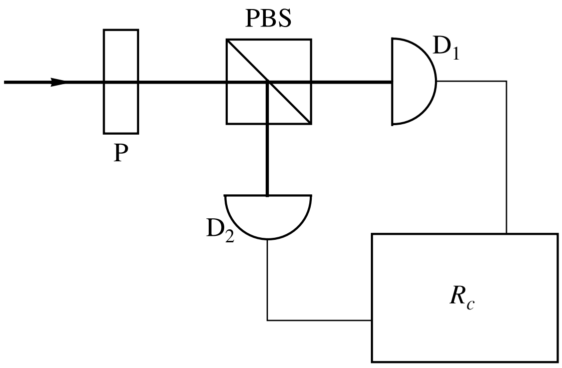

Fig. 1. Schematic diagram for observation of "latent polarization" [15]. After the polarization transformer P, the beam splits by the polarization beam splitter PBS and is directed to photodetectors D1 and D2. The coincidence count rate R_c may depend on the polarization transformation even if the intensities registered by the detectors are independent of it.

$\mathbf{k}'_\perp$ are the transverse components of the wave vectors. In this case, the summation over $\mathbf{k}'$ in Eq. (2) disappears, and the second term describes an entangled state of the two photons. This state becomes a Bell state if the sum over $\mathbf{k}$ contains only two terms.

Depending on the parameters in which "entanglement" occurs (frequency, direction of the wave vector (scattering angle), polarization), we can single out the following three classes of Bell states generated during spontaneous parametric scattering.

1. Polarization-angle Bell states. The signal and idler photons are emitted at different angles θ and θ' to the pumping wave vector; polarization for each photon is not specified, but there exists a correlation (entanglement) between the two polarizations. The two-photon part of the vector of state in this case has the form

$$|H_\theta V_{\theta'}\rangle \pm |V_\theta H_{\theta'}\rangle \quad \text{or} \quad |H_\theta H_{\theta'}\rangle \pm |V_\theta V_{\theta'}\rangle,$$

where symbols H and V denote the horizontal and vertical polarizations. Such states were realized for the first time by using type II synchronism[1] [6]. Subsequently, a more convenient scheme [7] was proposed, in which analogous states were obtained as a result of interference of biphotons generated in two successively arranged crystals with type I synchronism.

2. Frequency-angle Bell states. In the case of noncollinear nondegenerate spontaneous parametric scattering with type I synchronism for small frequency detuning of the signal and idler photons from the pumping frequency, we can single out such directions of scattering θ and θ', in which a signal photon of frequency ω as well as an idler photon of frequency ω' are emitted. In this case, the two-photon part of the vector of state has the form

$$|\omega_\theta \omega'_{\theta'}\rangle \pm |\omega'_\theta \omega_{\theta'}\rangle,$$

i.e., Bell states $\Psi^\pm$ are generated. The experimental realizations of such states are described in [8].

3. Finally, it is possible to prepare polarization-frequency Bell states of the form

$$|H_\omega V_{\omega'}\rangle \pm |V_\omega H_{\omega'}\rangle \quad \text{or} \quad |H_\omega H_{\omega'}\rangle \pm |V_\omega V_{\omega'}\rangle. \qquad (3)$$

An experiment in which such states were obtained is described in [9], where the interferometric method of preparing Bell states was used. The modes ω and ω' differed not only in frequency, but also in the direction of propagation (two-beam regime). However, the preparation of states (3) in the one-beam regime realized in a collinear spontaneous parametric scattering is of special interest. The one-beam regime of two-photon light generation is used comparatively rarely in quantum optics, although it is this regime which is of interest for data transmission. In addition, it will be shown below that such Bell states may possess interesting features as regards their polarization properties. Namely, light in one of the states (3) turns out to be nonpolarized in all orders in field.

LATENT POLARIZATION OF LIGHT

Many authors (see, for example, [10-12]), considered the polarization of light in higher (than second) orders in field. It was shown in [11] that a situation is possible, when light is not polarized in the second order in the field, but exhibits polarization dependences in the fourth-order (in field) correlation functions. Such a property (latent polarization) is observed, for example, in parametric scattering radiation with a collinear frequency-degenerate type II synchronism, which was demonstrated experimentally in [13]. A classical analogue of this effect was also proposed in [11], and its experimental realization is described in [14].

The schematic diagram of experimental observation of latent polarization is shown in Fig. 1 [15]. The radiation under investigation is directed to the polarization beam splitter PBS with a pair of photodetectors D1 and D2 mounted at the exits. In front of the beam splitter, a system of phase plates (two such plates are sufficient) P is mounted, which makes it possible to carry out any polarization transformation. If light is not polarized in the second order in field, the intensity registered by each of the detectors remains unchanged under any polarization transformation.

Let us suppose that a correlation function of the form

$$G^{(2)}_{HV}(\tau) = \langle E^{(-)}_H(t) E^{(-)}_V(t+\tau) E^{(+)}_H(t) E^{(+)}_V(t+\tau)\rangle, \quad (4)$$

is measured in an experiment, where $E^{(-)}$ and $E^{(+)}$ are respectively the negative-frequency and positive-frequency fields, the subscripts H and V denoting the lin-

[1] In the case of type I synchronism, the signal and idler photons are polarized identically; in the case of type II synchronism, their polarizations are orthogonal.

ear horizontal and vertical polarization modes. This quantity, which characterizes intensity correlation in the polarization modes, may depend on polarization transformation in front of the beam splitter even for light nonpolarized in the second order. In order to measure the correlation function (4), signals from detectors are directed to the input of the photocounting coincidence circuit; the coincidence count rate R_c is determined by the value of $G_{HV}^{(2)}$. For example, the correlation function (4) in [13] was measured for polarization transformations carried out by rotating the half-wave plate. If two-photon light was present at the input, modulation of the coincidence count rate was observed with a high visibility.[2] In the presence of a classical source (e.g., radiation from two orthogonally polarized lasers with independent phase fluctuations [14]) at the input, a modulation of $G_{HV}^{(2)}$ with a 50% visibility is observed in the experiment.

Let us now consider four polarization-frequency Bell states (3). It is well known that the singlet state Ψ^- is invariant to any polarization transformations [16]. It should not display any polarization dependence during measurements of moments of any order in field, including the correlation function (4). It can also be noted that the state Φ^+ is invariant to rotations of the polarization plane. Consequently, no modulation in the number of coincidence must be observed for such a state (as well as for the Ψ^- state) in the experiment described in [13].

Thus, light in the singlet Bell state Ψ^- is nonpolarized in the second as well as fourth order in the field. Since all moments for two-photon light can be expressed in terms of second- and fourth-order moments, light in state Ψ^- is nonloparized in all orders in the field. Such light can be referred to as completely nonpolarized.

4. “SCALAR LIGHT”

The state of light Ψ^- is close to the state of polarization-scalar light proposed in [10] (see also [17]). A transition from the state of polarization-scalar light to state Ψ^- occurs in the limit of a low pumping power or a small parametric transformation coefficient. For polarization-scalar light, fluctuations of all Stokes parameters must be suppressed.

The fluctuations of Stokes parameters can be easily calculated for all four polarization-frequency Bell states. It turns out as a result that fluctuations of the third Stokes parameter are suppressed in state Φ^+ (ΔS_3^2 = 0); ΔS_2^2 = 0 in state Φ^-, ΔS_1^2 = 0 in state Ψ^+, while in the singlet state Ψ^-, the fluctuations of all the three Stokes parameter are suppressed: $\Delta S_1^2 = \Delta S_2^2 = \Delta S_3^2 =$ 0. However, the measurements of fluctuations of Stokes parameters for biphoton light would require very rapid detectors (with a time resolution of the order of reciprocal width of the parametric scattering spectrum, i.e., of the order of hundreds of femtoseconds). Such detectors are not available at present. The suppression of fluctuations of the Stokes parameters can be obtained with the help of detectors with a nanosecond time resolution, but only in the case of parametric oscillation of light, when the emission spectrum is considerably narrower than for spontaneous parametric scattering. In this study, we used the spontaneous scattering regime; accordingly, we measured not the fluctuations of the Stokes parameters, but correlation functions of intensity.

[2] In such an experiment, the visibility must be 100% according to the theory.

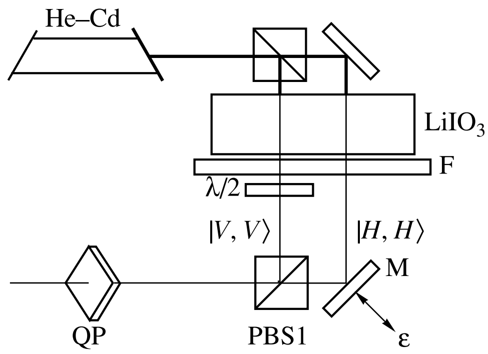

Fig. 2. Schematic diagram of experiment. Parametric scattering in the collinear frequency-nondegenerate regime with type I synchronism occurs in two spatially separated regions in a lithium iodate crystal. Biphoton radiation at the crystal exit is in the state $|H_\omega H_{\omega'}\rangle$ in both beams. In the right beam, polarization is rotated with the help of a $\lambda/2$ plate. The phase ε between the beam is controlled by mirror M. The phase incursion between the extraordinarily polarized wave and the ordinarily polarized wave at frequency ω in the quartz plate QP exceeds the corresponding phase incursion at frequency ω' by π.

5. PREPARATION AND ANALYSIS OF POLARIZATION-FREQUENCY BELL STATES

The schematic diagram of the experiment on obtaining four polarization-frequency Bell states is presented in Fig. 2. Continuous pumping (radiation of helium-cadmium laser at a wavelength of 325 nm) through a nonpolarization beam splitter is directed to the interferometer whose both arms contain a lithium iodate crystal. In the crystal, lights experiences spontaneous parametric scattering with a nondegenerate collinear type I synchronism; as a result, biphoton radiation in state $|H_\omega H_{\omega'}\rangle$ is present in both arms behind the crystal. The wavelength of the signal and idler photons are 635 and 665 nm, respectively. Pumping radiation behind the crystal is cut off by filter F. A half-wave plate in one of the arms rotates polarization through $\pi/2$, transforming the beam state into $|V_\omega V_{\omega'}\rangle$, and both beams meet without loss in the polarization beam splitter PBS1. Mirror

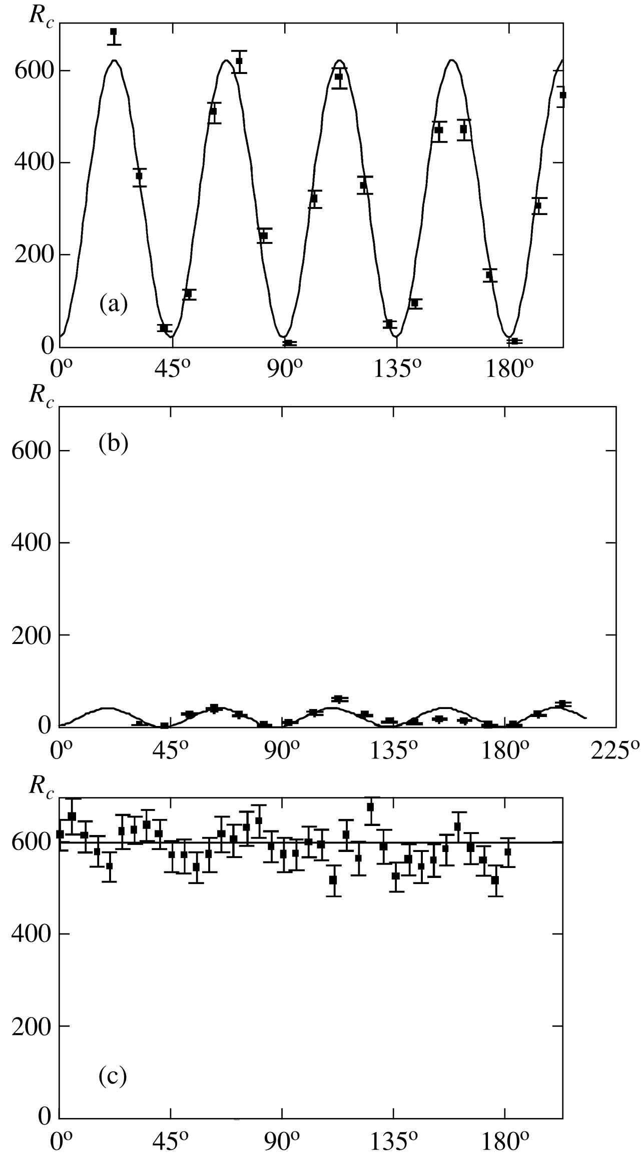

Fig. 3. Dependence of the coincidence count rate (number of coincidences during 200 s) on the angle of rotation of the $\lambda/2$ plate for (a) Φ^-, (b) Φ^+, and (c) Ψ^-.
The solid curve in (a) corresponds to relation (10) with an added constant background, which corresponds to a visibility of 94%. The solid curve in (b) is plotted under the assumption that the intensities of biphoton beams differ by 20%; in this case, calculations give the same dependence as in (a), but with an amplitude smaller by a factor of 20. The theoretical dependence in (c) is depicted by the straight line.

M in the interferometer can be displaced with the help of a piezoelectric feed. The state of the biphoton field at the exit of the interferometer has the form

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|H_\omega H_{\omega'}\rangle + e^{-i\varepsilon}|V_\omega, V_{\omega'}\rangle), \quad (5)$$

where phase ε can be varied by displacing mirror M. For $\varepsilon = 0$, Bell state Φ^+ is formed, while for $\varepsilon = \pi$, we have Bell state Φ^-. State Ψ^+ can be obtained from Φ^- with the help of a half-wave plate oriented at an angle of $\pi/8$.

Bell states Φ^+, Φ^-, and Ψ^+ are analogues of states obtained in [18] by using the same experimental setup, but for the degenerate regime of parametric scattering. As we pass to the degenerate scattering regime, state Φ^+ is transformed into a pair of correlated photons with right-circular and left-circular polarizations, state Φ^- is converted into a pair of linearly polarized photons at angles $\pi/4$, while state Ψ^+ is transformed into a pair of photons polarized along the vertical and the horizontal.

The singlet state Ψ^- has no analogue in the degenerate regime since it is antisymmetric relative to the transposition of photons in a pair. In order to prepare this state, a special phase plate made of a quartz crystal (QP) was used in experiments. The thickness of this plate satisfied the following condition: the phase incursion between the ordinary and extraordinary waves at frequency ω differs from the corresponding phase incursion at frequency ω' by π. If the state $\Psi^+ = |H_\omega V_{\omega'}\rangle + |V_\omega H_{\omega'}\rangle$ exists at the entrance of such a plate, and its optical axis is oriented along the vertical or horizontal, the state behind the plate has the form $\Phi^- = |H_\omega V_{\omega'}\rangle - |V_\omega H_{\omega'}\rangle$ to within an insignificant common phase. In order to obtain state Ψ^-, phase ε in the interferometer was set equal to π so that the state $\Phi^- = |H_\omega H_{\omega'}\rangle - |V_\omega V_{\omega'}\rangle$ was formed at the exit of the interferometer. In the basis *XY* turned through $\pi/4$ relative to the basis *HV*, state Φ^- is transformed into Ψ^+:

$$|H_\omega H_{\omega'}\rangle - |V_\omega V_{\omega'}\rangle = |X_\omega Y_{\omega'}\rangle + |Y_\omega X_{\omega'}\rangle.$$

Plate QP is mounted at the exit of the interferometer so that its optical axis is oriented along direction *X*. Behind the plate, the state in the basis *XY* was transformed into Ψ^-; consequently, in view of its invariance to polarization transformations, this state remained unchanged in any polarization basis.

The measurements for the four polarization-frequency Bell states obtained by us, measurements were made according to the scheme proposed in [15]: the value of $G_{HV}^{(2)}$ was measured depending on the polarization transformation in front of beam splitter (see Fig. 1). In order to single out small scattering angles, an aperture was used. Since noise radiation was also present at the entrance of the detecting elements of the setup in addition to radiation from spontaneous parametric scattering, an interference filter of width 40 nm with transmittance peak at a wavelength of 650 nm. The filter transmitted both signal and idler radiation. Avalanche photodiodes operating in the photon count mode were used as detectors, and the resolution of the coincidence scheme was 1.5 ns.

The role of polarization transformers was played by $\lambda/2$ and $\lambda/4$ plates. Figure 3 shows the dependences obtained for *G* during the rotation of the $\lambda/2$ plate for

Bell states Φ^-, Φ^+, and Ψ^-. The dependence for the Ψ^+ state is not shown since this state is transformed to Φ^- by rotating the basis through $\pi/4$; consequently, the angular dependence for this state is the same as for Φ^- to within a shift by $\pi/8$ along the abscissa axis.

It should be noted at the very outset that all the experimentally obtained entangled states were nonpolarized in the second order in field: under polarization transformations by the $\lambda/4$ and $\lambda/2$ plates, the intensity of the beam detected by each detector (see Fig. 1) remained practically unchanged.[3]

It can be seen that the state Φ^- possesses "latent polarization" (Fig. 3a): upon the rotation of the $\lambda/2$ plate, the number of coincidences R_c oscillates with a high visibility (94%). The dependence of R_c on the angle of rotation χ of the plate can be easily derived using expression (4) for the correlation function and writing state Φ^- in the form

$$\begin{aligned}\Phi^- &= |H_\omega H_{\omega'}\rangle|V_\omega V_{\omega'}\rangle \\ &= [a_H^\dagger(\omega)a_H^\dagger(\omega') - a_V^\dagger(\omega)a_V^\dagger(\omega')]|\text{vac}\rangle,\end{aligned} \tag{6}$$

where $a^\dagger_{H,V}(\omega, \omega')$ are the photon creation operators in the polarization modes H and V and in frequency modes ω and ω'. Now, we express the fields in relation (4) in terms of the creation operator and consider that the left-hand side of Eq. (4) is Hermitian conjugate to the right-hand side. Averaging in Eq. (4) should be carried out over the state $\Phi(\chi)$ obtained from Φ^- as a result of action of the plate. This gives

$$\begin{aligned}&G^{(2)}_{HV}(\tau) \\ &= \left|\iint d\omega_1 d\omega_2 a_H^\dagger(\omega_1)e^{-i\omega_1 t}a_V^\dagger(\omega_2)e^{-i\omega_2(t+\tau)}|\Phi(\chi)\rangle\right|^2.\end{aligned} \tag{7}$$

Using the Jones matrix for the $\lambda/2$ plate oriented at angle χ [15],

$$D = \begin{pmatrix} i\cos(2\chi) & i\sin(2\chi) \\ i\sin(2\chi) & -i\cos(2\chi) \end{pmatrix},$$

and expressing the creation operators in front of the plate in terms of the creation operators behind the plate, we obtain the following expression for state $\Phi(\chi)$ accurate to an insignificant phase factor:

$$\begin{aligned}\Phi(\chi) &= \cos(4\chi)(|H_\omega H_{\omega'}\rangle - |V_\omega V_{\omega'}\rangle) \\ &\quad - \sin(4\chi)(|H_\omega V_{\omega'}\rangle + |V_\omega H_{\omega'}\rangle).\end{aligned} \tag{8}$$

After integration, this equation will contain only the terms corresponding to frequencies ω and ω'. Substituting Eq. (8) into relation (7), we obtain

$$G^{(2)}_{HV}(\tau) = 4\cos^2\frac{\omega-\omega'}{2}\tau\sin^2(4\chi). \tag{9}$$

[3] Intensity modulation did not exceed 15%.

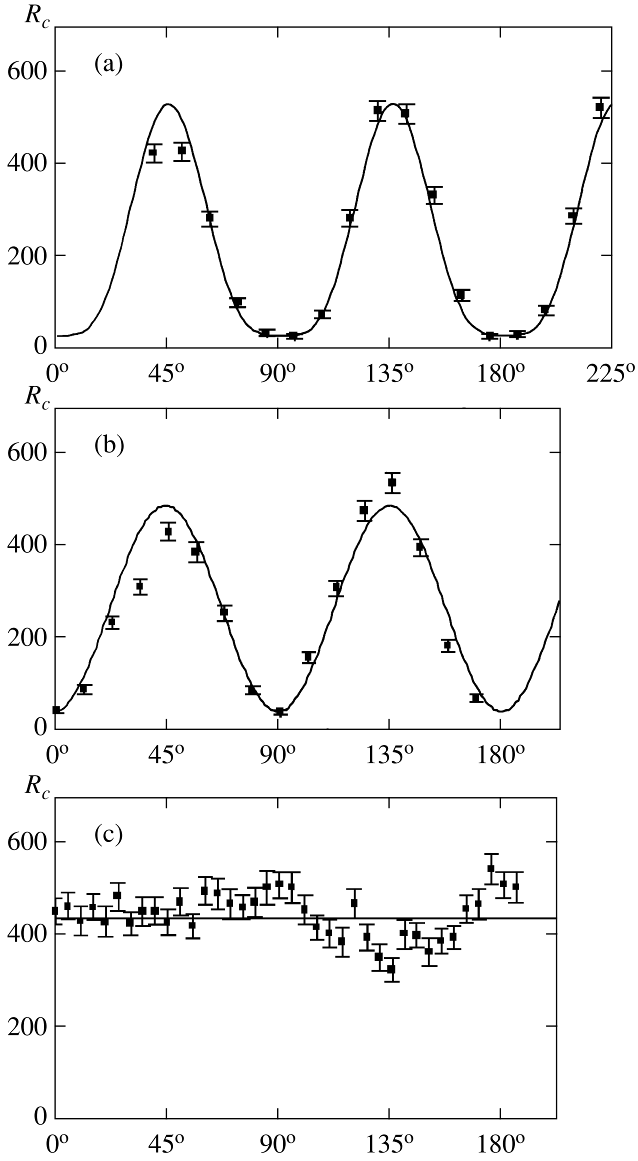

Fig. 4. Dependence of the number of coincidences on the angle of rotation of a $\lambda/4$ plate for (a) Φ^-, (b) Φ^+, and (c) Ψ^-. Theoretical curves are plotted from relations (11) (a) and (12) (b) with an added background, taking into account the departure of visibility from 100%. The visibility is 93%. The theoretical dependence in (c) is depicted by the straight line.

(the contribution resulting from averaging gives only the second term in Eq. (8)).

The rate of coincidence count in the scheme presented in Fig. 1 is determined by the integral of $G^{(2)}_{HV}(\tau)$ with respect to τ in the limits determined by the time resolution T of the coincidence circuit, which is considerably longer than the period of oscillations of the first factor in Eq. (9). This gives

$$R_c\left(\Phi^-, \frac{\lambda}{2}\right) \propto \sin^2(4\chi), \tag{10}$$

which is in good agreement with the experimental results (Fig. 3a).

If state Φ^+ is formed at the entrance of the polarization transformer, the coincidence count rate is independent of the angle of rotation of the half-wave plate; it can easily be verified that state Φ^+ does not change in this case. The coincidence count rate remains close to zero since the polarization anticorrelation effect takes place [19]. Accordingly, the coincidence count rate in Fig. 3b is smaller than the count rate for state Φ^- by more than an order of magnitude (Fig. 3a). The observed modulation is apparently due to the fact that biphoton beams in different arms of the interferometer had slightly different intensities. For example, if the contributions to the coincidence count rate from the two arms differ by 20%, we can obtain for R_c a dependence analogous to (10), but with an amplitude smaller by a factor of 20.

For the case when state Ψ^- was formed in front of the plate, a high coincidence count rate independent of χ was observed (Fig. 3c). Calculations similar to those described above give in this case a constant value for R_c, equal to the maximum of function (10).

The results presented in Fig. 4 were obtained by using a $\lambda/4$ plate as a polarization transformer. In this case, calculations give the following dependence of state Φ^- at the entrance to the plate:

$$R_c\left(\Phi^-, \frac{\lambda}{4}\right) \propto \sin^4(2\chi). \quad (11)$$

This dependence is in good agreement with the experimental dependence (Fig. 4a).

The change in the value of χ for state Φ^+ at the plate entrance leads to complete modulation of the coincidence count rate (Fig. 4b). Calculations for this case give the following dependence:

$$R_c\left(\Phi^+, \frac{\lambda}{4}\right) \propto \sin^2(2\chi). \quad (12)$$

Finally, for state Ψ^- at the entrance of the $\lambda/4$ plate, the coincidence count rate modulation during the rotation of the plate is virtually absent (Fig. 4c).

Our measurements revealed that biphoton light in state Ψ^- does not possess “latent polarization”, i.e., is nonpolarized in the second as well as fourth order in the field. All the remaining Bell states exhibit latent polarization.

6. CONCLUSIONS

Thus, biphoton light in a singlet polarization-frequency Bell state turns out to be completely nonpolarized and is a polarization-scalar light. Such a state of light was obtained experimentally as well the remaining three polarization-frequency Bell states. It is convenient to use “one-beam” geometry in this case since it makes it possible to use biphoton light for data transmission by sending the signal and idler photons through the same optical fiber. It can be expected that such states will be applied for coding and transmission of quantum information.

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SPELL: splitter, gedanken, eigenstates, teleportation, half-wave