PHYSICAL REVIEW A, VOLUME 64, 011801(R)

Anticorrelation effect in femtosecond-pulse pumped type-II spontaneous parametric down-conversion

Yoon-Ho Kim,* Vincenzo Berardi,† Maria V. Chekhova,‡ and Yanhua Shih
Department of Physics, University of Maryland, Baltimore County, Baltimore, Maryland 21250
(Received 29 January 2001; published 1 June 2001)

We report an experimental demonstration of an anticorrelation effect in femtosecond-pulse pumped type-II spontaneous parametric down-conversion. Our experimental data, which is different from that of Atatüre *et al.* [Phys. Rev. Lett. **83**, 1323 (2000)], confirmed the shallow *symmetric* ''dip'' that is predicted theoretically by Keller and Rubin [Phys. Rev. A **56**, 1534 (1997)] and Grice and Walmsley [Phys. Rev. A **56**, 1627 (1997)]. We show in this paper that the asymmetric dip observed in the literature is an artifact, which is caused by the asymmetric optical elements introduced into the beam path *after* the down-conversion process. The ''partial distinguishability'' theory suggested by Atatüre *et al.* is therefore incorrect.

DOI: 10.1103/PhysRevA.64.011801 PACS number(s): 42.50.Dv, 03.67.−a, 42.65.Yj

Spontaneous parametric down-conversion (SPDC) [1,2] is by far the most accessible source of entangled particle pairs [3]. SPDC is a nonlinear optical process in which an incident pump photon is converted into a pair of daughter photons, usually called the *signal* and the *idler*, with a very low probability. In type-I SPDC, the photon pairs are polarized in the same direction (both o-polarized); and in type-II SPDC, the photon pairs are polarized orthogonally (one o-polarized and the other e-polarized). The photon pairs are explicitly correlated in energy and time (polarization as well in type-II SPDC).

Among many interesting quantum interference effects in SPDC, the anticorrelation effect (or commonly called the anticorrelation ''dip''), which was first reported for type-I SPDC in Ref. [4] and for type-II SPDC in Refs. [3,4], is one of the first to be observed. [This effect plays a crucial role in preparing maximally polarization-entangled two-photon states (Bell states) using SPDC [3].]

To observe the dip effect in type-I SPDC, signal and idler photons are sent to different input ports of a 50–50 beam splitter [3,4]. A pair of detectors registers photons in the output modes of the beam splitter, so that each detector can register both transmitted or reflected photons from signal or idler modes. The coincidence counting rates $R_c(\tau)$ of the two detectors are measured as a function of the delay τ introduced between the signal and idler photons before the beam splitter. When the delay τ is less than the coherence time δt_c, which is defined by the bandwidth of the spectral filters inserted in front of the detectors, i.e., $\tau<|\delta t_c|$, a typical dip is observed: the coincidence counting rates drop down below the level of coincidence counts with $\tau\geqslant|\delta t_c|$, i.e., $R_c(\tau<|\delta t_c|)<R_c(\tau\geqslant|\delta t_c|)$, and even reach ''zero'' when the delay $\tau=0$.

In type-II SPDC, the dip effect is observed by introducing a delay τ between e- and o-polarized photons [5]. The e-o delay can be introduced, for example, by using a set of quartz plates. The collinear SPDC beam is split into two spatial modes by using a nonpolarizing 50-50 beam splitter. In addition to the spatial modes created by the 50-50 beam splitter, the signal and the idler also belong to the different polarization modes. Therefore, to observe the dip effect, one has to ''erase'' this polarization information by using a pair of 45° polarization projectors. Also, the dip has a peculiar triangular shape with the base width DL, where $D=1/u_o-1/u_e$ is the inverse group velocity difference for signal and idler photons in the crystal and L is the crystal length [6]. The minimum of the dip corresponds to the delay $\tau=DL/2$ [5,6]. Note that if the orientations of the analyzers differ by 90°, the triangular dip becomes the triangular peak with the base width DL.

Usually, the dip is interpreted as the photon-bunching effect at the beam splitter: when the signal and the idler photons overlap at the beam splitter, two photons ''stick'' together and always go to the same detector giving no coincidence counts. This picture, however, is not correct in general. Pittman *et al.* have recently shown that the dip can be observed even if the signal-idler photon pairs do not overlap at the beam splitter [7]. Reference [7] clearly demonstrated the entangled nature of the photon pair, which we may call the ''biphoton.''

The dip or ''peak'' effect is the result of quantum interference between the two Feynman alternatives (biphoton amplitudes): the signal-idler both reflected (or transmitted-reflected in the type-II case) at the beam splitter or both transmitted (or reflected-transmitted in the type-II case) at the beam splitter. If the two Feynman alternatives are made indistinguishable, quantum interference occurs and the interference dip is observed as a result. All these effects have been observed by using the SPDC pumped by a cw laser.

Recently, femtosecond laser pulses have been used to pump the SPDC process. In femtosecond-pulse pumped type-II SPDC, theoretical calculations predict very poor vis-

*Present address: Center for Engineering Science Advanced Research, Oak Ridge National Laboratory, Oak Ridge, TN 37830. Email address: yokim@umbc.edu

†Permanent address: INFM–Dipartimento Interateneo di Fisica, University of Bari, Bari, Italy.

‡Permanent address: Department of Physics, Moscow State University, Moscow, Russia.

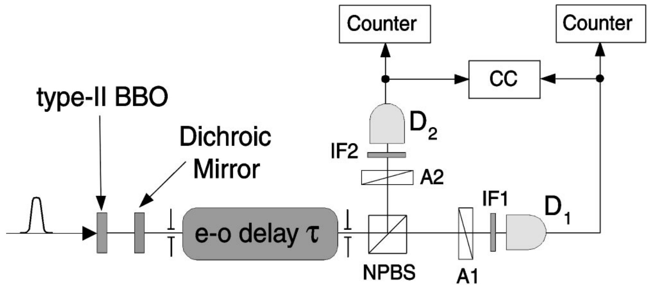

FIG. 1. The experimental setup. Type-II SPDC is separated from the residual UV pump beam by using a dichroic mirror. A pinhole selects the collinear SPDC. The coincidence counting rates are monitored as a function of the e-o delay τ. See text for details.

ibility for the anticorrelation effect when a thick nonlinear crystal is used [8]. The dip in this case has the same base width DL as for the cw-pump case, but its depth decreases with the increase of the crystal thickness. The dip completely vanishes if the pulse duration T_p is much less than DL. The reason is that the short pump pulse acts as a ''clock'' for the SPDC process [8]: having registered a pair of photons, one can know for sure at which location of the crystal the pair was born. The delay $\tau = DL/2$ compensates for signal-idler group velocity difference only for pairs born in the center of the crystal; any other delay $0 < \tau < DL$ gives a compensation for some pairs but not for all pairs, so the compensation can never be complete [9]. That is why the dip predicted by the theory is *flat*, *shallow*, and *symmetric*. The visibility of the dip can be increased either by using a thin crystal or by using narrow-band spectral filters in front of the detectors [11].

In this Rapid Communication, we present an experimental demonstration of the anticorrelation effect for femtosecond-pulse pumped type-II SPDC from relatively thick crystals (the ratio T_p/DL is approximately 0.2∼0.4, depending on the experimental conditions). The experimental setup is shown in Fig. 1. As a pump, we use the second harmonic of a Spectra-Physics Tsunami femtosecond laser system. The central wavelength is 400 nm and the pulse duration is $T_p \approx 80$ fsec. Type-II SPDC is obtained in a BBO crystal cut for collinear frequency-degenerate phase matching. Two different crystals are used: one with a thickness of 1.1 mm and the other with a thickness of 2 mm. After the crystal, the UV pump beam is removed by using a dichroic mirror, which reflects the strong residual pump beam while transmitting the SPDC radiation of central wavelength 800 nm. Both signal and idler collinear beams are split by a 50-50 beam splitter. The delay τ between signal (e ray) and idler (o ray) is introduced before the beam splitter.

Single-photon counting detectors (D_1 and D_2) are placed at the output ports of the beam splitter and the coincidence counts between the two detectors are recorded as a function of τ. The coincidence window in this experiment was 3 nsec. Polarization analyzers (A_1 and A_2) placed before the detectors are set at 45° to ''erase'' the which-path information available in polarization modes. Interference filters (IF_1 and IF_2) can be placed before the detectors to see the effects of spectral filtering. In this experiment, the spectral filters are used mainly to cut the background noise from the pump beam. To make sure no effects of spectral filtering are present, the full width at half maximum (FWHM) of the spectral filters use in this experiment was 40 nm.

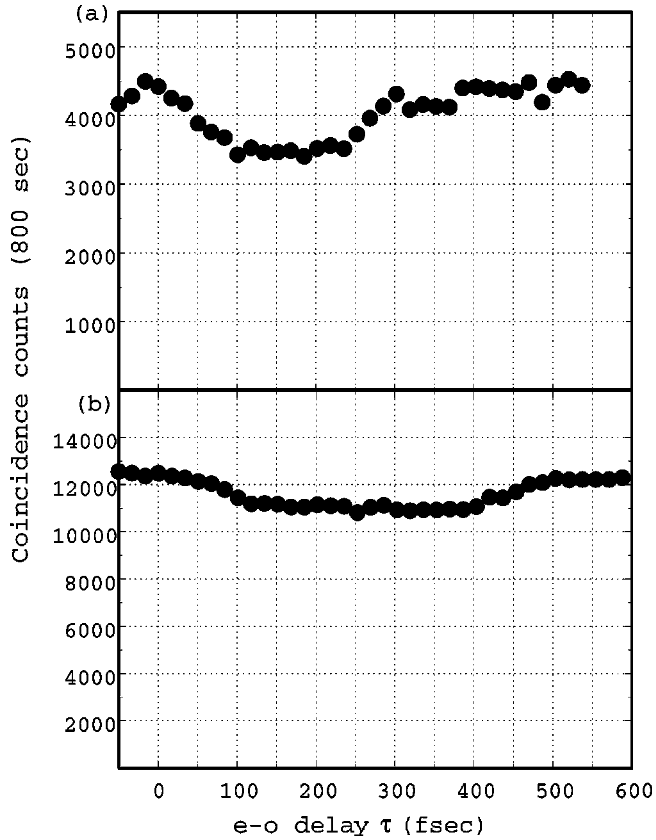

FIG. 2. The results obtained with the setup shown in Fig. 1 for 40-nm filters. (a) 1.1-mm (BBO) and (b) 2-mm BBO. In agreement with the theory, a flat symmetric dip is observed.

The experimental data are shown in Fig. 2. As predicted by the theory [8], symmetric and flat dip is observed for both 1.1-mm and 2-mm crystals when 40-nm FWHM filters are used. The width of the dip is in agreement with the theoretical prediction. The visibility is slightly lower than given by the theory, but this is due to slight misalignment in the e-o delay part of the setup. (We have used air delay in this experiment.)

The results are, however, different from the results reported by Atatüre *et al.* [12]. In Ref. [12], Atatüre *et al.* reported that the type-II SPDC dip in the case of femtosecond-pulse pump showed a strange asymmetric shape when a thick crystal was used. To explain this unpredicted asymmetry in type-II dip, Atatüre *et al.* introduced a parameter (d_{eff}), which is supposed to be responsible for the ''partial distinguishability'' in femtosecond pulse pumped type-II SPDC. However, such partial distinguishability is already accounted for in the theory of pulsed type-II SPDC and the net effect is the reduction of visibility, see Ref. [8]. Moreover, the parameter d_{eff} introduced by Atatüre *et al.* is not connected with any physical properties of the crystal or the pump pulse. This means that d_{eff} is simply a fitting parameter that is introduced arbitrarily to the standard theory of type-II SPDC to fit the data.

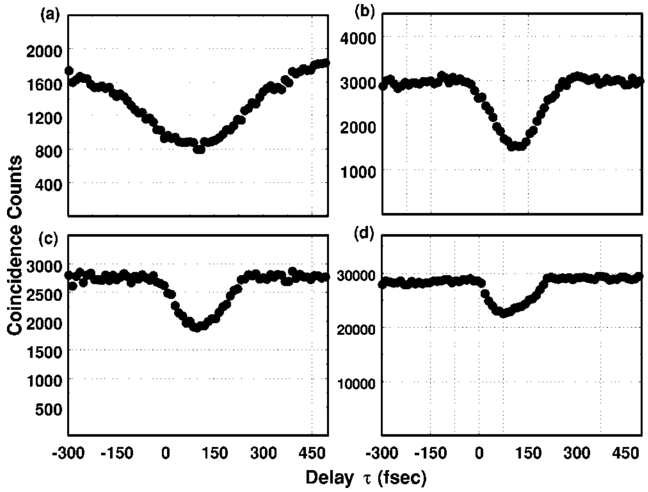

FIG. 3. Experimental data with the dichroic mirror replaced by a prism. The thickness of the type-II BBO crystal is 1.1 mm. (a) 3-nm filters are used and 100-sec data accumulation time for each point, (b) 10-nm filters and 30-sec data collection time, (c) 40-nm filters and 60-sec data accumulation time, and (d) no filters are used and 180-sec data accumulation time.

Comparing our experimental setup with the one used in Ref. [12], we see that there is a difference in the way in which the SPDC beam is separated from the residual pump beam: while we use a dichroic mirror that introduces no asymmetry into the setup, the authors of Ref. [12] used a prism that introduced asymmetry.

Our natural assumption is that the prism affects the spatiotemporal properties of SPDC and causes the asymmetry observed in Ref. [12]. To check this assumption, we replaced the mirror by a prism. The results are shown in Figs. 3 and 4.

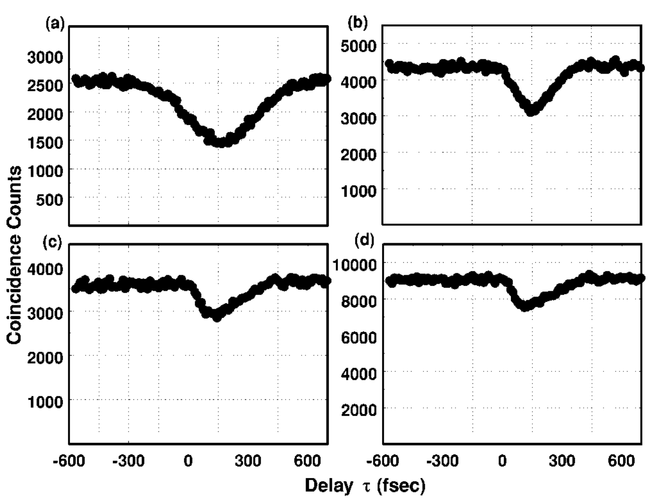

FIG. 4. Experimental data with the dichroic mirror replaced by a prism. The thickness of the type-II BBO crystal is 2 mm. (a) 3-nm filters and 50-sec data collection time, (b) 10-nm filters and 20-sec data collection time, (c) 40-nm filters and 30-sec data collection time, and (d) no filters. The data are collected for 30-sec each point. The asymmetry is clearly demonstrated. Note that no difference is observed between the results obtained with 40-nm filters and with no filters at all.

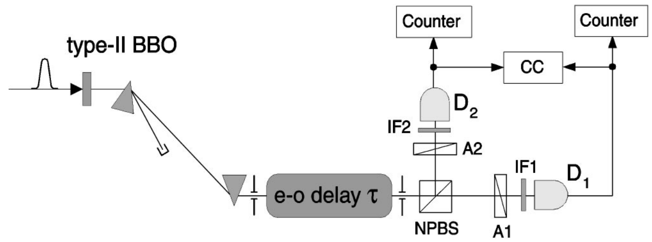

FIG. 5. A pair of prisms is used to separate the pump from the SPDC. The use of the second prism is to compensate any effect of the first prism on the quantum state of type-II SPDC.

When strong spectral filtering is made, the visibility is increased and the dip looks symmetric. However, when the FWHM of the spectral filters is big (40 nm) or no spectral filtering is made, the dip is clearly asymmetric. This means that the asymmetry is actually caused by the asymmetry introduced by the prism, rather than some ''unknown'' partial distinguishability of the down-conversion process itself.

Before concluding that the asymmetry is simply due to the prism, we have performed another experiment. In this experiment, a second prism is used to compensate the effect of the first prism, see Fig. 5. The data are shown in Fig. 6 and this is to be compared with Fig. 4(c). One can clearly see that the strong asymmetry shown in Fig. 4(c) has disappeared in Fig. 6.

The implication of the data presented in this paper is clear. The asymmetric dip observed in femtosecond-pulse pumped type-II SPDC is not due to the ''partial decoherence'' of the down-conversion process as suggested by Atatüre *et al.* [12]. The asymmetric dip is related to the asymmetric optical elements that are introduced into the beam path after the down-conversion crystal.

In summary, we have experimentally demonstrated that the asymmetric dip in femtosecond-pulse pumped type-II

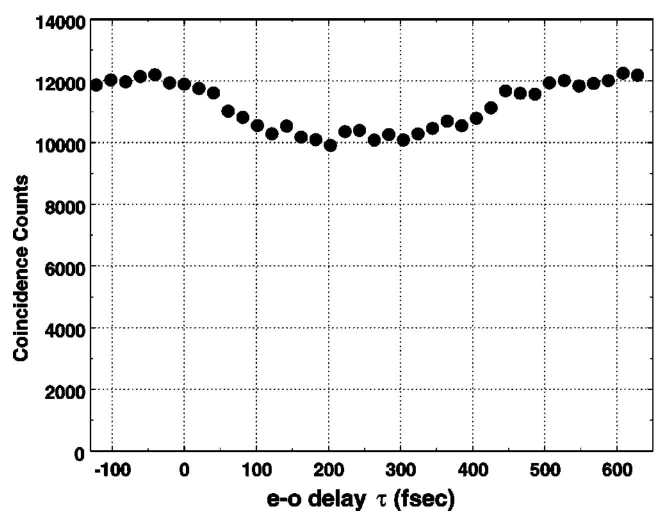

FIG. 6. The results obtained for the setup shown in Fig. 5. The 2-mm BBO crystal and 40-nm filters are used. The asymmetry observed in Fig. 4(c) is now absent. The data accumulation time is 5000 sec for each point. The coincidence counts are corrected by using the single counts of one of the detectors to account for the variation of the pump power.

SPDC observed in the literature is an artifact of the specific experimental setup. An externally introduced asymmetry is responsible for the asymmetric dip. The current theory of SPDC developed in Ref. [8] requires no modification and the predictions of the theory are confirmed experimentally [13].

We would like to thank M.H. Rubin for suggesting the two-prism experiment. We also acknowledge valuable discussions with A. Garuccio. This work was supported in part by the Office of Naval Research, ARDA, and the National Security Agency.

[1] D. N. Klyshko, *Photons and Nonlinear Optics* (Gordon and Breach, New York, 1988).

[2] D. C. Burnham and D. L. Weinberg, Phys. Rev. Lett. **25**, 84 (1970).

[3] C. O. Alley and Y. H. Shih, in *Proceedings of the 2nd International Symposium on Foundations of Quantum Mechanics*, edited by M. Namiki (Physical Society of Japan, Tokyo, 1986); Y. H. Shih and C. O. Alley, Phys. Rev. Lett. **61**, 2921 (1988).

[4] C. K. Hong, Z. Y. Ou, and L. Mandel, Phys. Rev. Lett. **59**, 2044 (1987).

[5] Y. H. Shih and A. V. Sergienko, Phys. Lett. A **186**, 29 (1994); **191**, 201 (1994).

[6] Here, we assumed no spectral filtering. If narrow-band Gaussian spectral filters ($\sigma < 1/|DL|$, where σ is the FWHM bandwidth of the spectral filter) are used in front of the detectors, the dip broadens and the shape of the dip approaches Gaussian. See M. H. Rubin, D. N. Klyshko, Y. H. Shih, and A. V. Sergienko, Phys. Rev. A **50**, 5122 (1994); T. B. Pittman, Ph.D. thesis, University of Maryland, 1996.

[7] T. B. Pittman, D. V. Strekalov, A. Migdall, M. H. Rubin, A. V. Sergienko, and Y. H. Shih, Phys. Rev. Lett. **77**, 1917 (1996).

[8] T. E. Keller and M. H. Rubin, Phys. Rev. A **56**, 1534 (1997); W. P. Grice and I. A. Walmsley, *ibid.* **56**, 1627 (1997).

[9] More precisely, the overlap between two biphoton amplitudes is very small in femtosecond-pulse pumped type-II SPDC from a thick crystal. The imperfect overlap has to do with the fact that femtosecond-pulse pumped type-II SPDC has a dramatically different biphoton wave function in contrast to cw-pumped type-II SPDC; see Refs. [8] and [10] for details.

[10] Y.-H. Kim, V. Berardi, M. V. Chekhova, A. Garuccio, and Y. H. Shih, Phys. Rev. A **62**, 043820 (2000); Y.-H. Kim, M. V. Chekhova, S. P. Kulik, M. H. Rubin, and Y. H. Shih, Phys. Rev. A (to be published); Y.-H. Kim, Ph.D. thesis, University of Maryland (2001).

[11] G. Di Giuseppe, L. Haiberger, F. De Martini, and A. V. Sergienko, Phys. Rev. A **56**, R21 (1997); A. V. Sergienko, M. Atatüre, Z. Walton, G. Jaeger, B. E. A. Saleh, and M. C. Teich, *ibid.* **60**, R2622 (1999).

[12] M. Atatüre, A. V. Sergienko, B. M. Jost, B. E. A. Saleh, and M. C. Teich, Phys. Rev. Lett. **83**, 1323 (2000).

[13] The effect of the asymmetric optical elements on the femtosecond-pulse pumped type-II SPDC is under investigation.