EXPERIMENTAL REALIZATION OF AN ALL OPTICAL SCHROEDINGER-CAT

Fabio Sciarrino, Daniele Pelliccia and Francesco De Martini

Dipartimento di Fisica and Istituto Nazionale di Fisica della Materia
Universita' "La Sapienza", Roma 00185, Italy

We report the first successful generation of entangled, *multiparticle* quantum superposition photon states: i.e. Schroedinger Cat states. The *information-preserving* (i.e. *coherence-preserving*) property of the *quantum-injected* Optical Parametric Amplifier transfers into the multi-particle regime the coherence property of any *single-particle* input qubit. This suggests for these states the name of *large-qubits* (*massive-qubits*). They are ideal objects for investigating the emergence of the classical world in quantum systems with increasing complexity, the decoherence processes and allow the practical optical implementation of 2 qubit logic-gates.

Since the golden years of quantum mechanics the interference of classically distinguishable quantum states, first introduced by the famous "Schroedinger Cat" (S-Cat) apologue [1], has been the object of extensive theoretical studies and recognized as a major paradigm of physics [2,3]. In modern times quantum information and quantum computation deal precisely with collective processes involving a multiplicity of interfering states, generally mutually entangled and rapidly de-phased by decoherence [4] For many respects the experimental implementation of this intriguing classical-quantum condition represents today an open problem in spite of recent successful studies carried out mostly with atoms and with photon-atom systems [5,6,7]. The present work reports the first experimental demonstration of an all-optical S-Cat, namely made of a multi-photon assembly in a quantum superposition state. The scheme is nearly decoherence-free and is based on the process of the *quantum injected* optical parametric amplification (OPA) of a single photon in a quantum superposition state, i.e, a *quantum bit* or *qubit* [8].

Conceptually, the adopted method consisted of transferring the well accessible and easily achievable *quantum superposition* condition affecting any input *single-particle* qubit to a "macroscopic", i.e. multi-particle amplified quantum-state. In virtue of the well known general *information-preserving* (i.e. *coherence-preserv*ing) property of the parametric amplification (OPA) the generated macroscopic state keeps the *same* quantum superposition character and the interfering capabilities of the input qubit, here optical-polarization $\vec{p}$ -encoded, thus realizing a genuine multi-photon S-Cat state [9].

Let us refer to the experimental apparatus: Figure 1. The OPA active element was a nonlinear (NL) crystal slab (BBO: β-barium borate), able to generate by spontaneous parametric down conversion (SPDC) $\vec{p}$ -entangled pairs of photons. Precisely, the OPA *intrinsic phase* was set as to generate by SPDC *singlet* entangled states on the output optical modes. The photons of each pair were emitted with equal wls λ =795nm over two spatial modes -k_1 and -k_2. The coherent *pump* field, associated with the spatial mode with wavevectors (wv) k_p and wl λ_p=397.5nm i.e. in the ultraviolet (UV) range of the spectrum, was provided by a Ti:Sa Coherent MIRA mode-locked pulsed laser coupled to a Second Harmonic Generator (SHG). The average UV power was 0.25 W, the pulse repetition rate was 76 MHz and the time duration of each UV pulse as well of the generated single photon pulses was τ =140 fs. Optionally, the peak power of the UV pulses could be raised by a factor $\gamma \approx 300$, and then the OPA gain g raised by a factor $\gamma^{1/2} \approx 17$ by adoption of a Ti-Sa regenerative amplifier Coherent REGA operating at 250 KHz. As shown in Fig.1 the UV pulse was reflected into the NL crystal by a μ-metrically **Z**-adjustable mirror M_p. Also one photon of each generated pair was *re-injected* through the mode k_1 into the NL crystal by the mirror M. A proper setting of **Z** secured the space-time overlapping into the NL crystal of the interacting re-injected pulses with wl's λ_p and λ. The OPA amplification gave rise on the output modes k_1 and k_2 to a bi-partite multi-particle entangled state: $|\Psi\rangle_{out}$ [9]. Various input $\vec{p}$ -states: $|\Psi\rangle_{in}=(\alpha|\Psi^{\alpha}\rangle+\beta|\Psi^{\beta}\rangle)$, $|\alpha|^2+|\beta|^2=1$ of the injected *single-particle* qubit, were prepared, via nonlocal correlations, by a Babinet-Compensator (B), by a set of Wave-Plates (WP), either $\lambda/2$ or $\lambda/4$, and by a polarizing beam-splitter (PBS) inserted on mode $-k_2$ before detection by D_T, this last providing the trigger pulse of the overall *conditional* experiment. The circles drawn on the surface of the Bloch-sphere in Fig. 2 show the transformations undergone in our experiment by the SPDC input qubit before re-injection into the OPA amplifier.

The S-Cat detection at the OPA output could be undertaken either on the same injection mode k_1, the "cloning mode", on the mode k_2, or on both output modes. We selected the second option since *any* interference effect registered on the output mode k_2 was by itself a clear-cut verification of the S-Cat condition. By the two detectors D_2 and D_2^* coupled to the two mutually orthogonal fields emerging from the output modes k_j, j=1,2 of PBS_2 the *first-order* correlation-functions $G_{2j}^{(1)}$ were measured [9,10]. As it is well known, precisely this quantity exhibits unambiguously the interference property of the S-Cat. The interference fringe patterns shown in Figs 3 and 4 are a clear evidence of such condition in two different dynamical regimes. Precisely, the patterns shown express the quantity $\Delta G_{21}^{(1)} =(G_{21}^{(1)} - G_{22}^{(1)})$ i.e., the difference between the correlation functions measured at the two outputs of PBS_2. It is easy to show that $\Delta G_{21}^{(2)}$ is free from noise while the two components $G_{21}^{(1)}$ and $G_{22}^{(1)}$ are affected by the quantum-noise, with a *signal-to-noise* ratio S/N=2, arising from the OPA amplification of the vacuum-field implied by the "quantum cloning" process [11]. Figure 3 refers to a low UV peak pump power corresponding to a OPA gain g=0.07. At this level approximately one single photon pair is generated by the OPA system and then, only 3 photons are making the S-Cat. The plots given by Fig.4 correspond to g=1.17 leading to a much "fatter" S-Cat, i.e. made of about 10 quantum-interfering photons. As said, in virtue of the *information-preserving* property of the quantum injected OPA the input *single-particle* qubit $|\Psi\rangle_{in}$ is "amplified" by our *quantum-injected* OPA system into: $|\Psi\rangle_{out}=(\alpha|\Psi^{\alpha}\rangle_{out}+\beta|\Psi^{\beta}\rangle_{out})$ where $|\Psi^{\alpha}\rangle_{out}$ and $|\Psi^{\beta}\rangle_{out}$ are normalized and mutually orthogonal *multi-particle* states. Several checks were performed on the performance of the apparatus, e.g. no interference effects were detected in absence of the injected *qubit*.

A thorough discussion of the interference properties of theses multiparticle, entangled states, as well on the, most important, de-coherence dynamics of the related S-Cat in standard environments will be discussed.

In summary, the first all-optical generator of Schroedinger Cat states has been fully demonstrated by the present work. These states are generated by a standard technique and are easily accessible at the output of a well known quantum optics OPA device.

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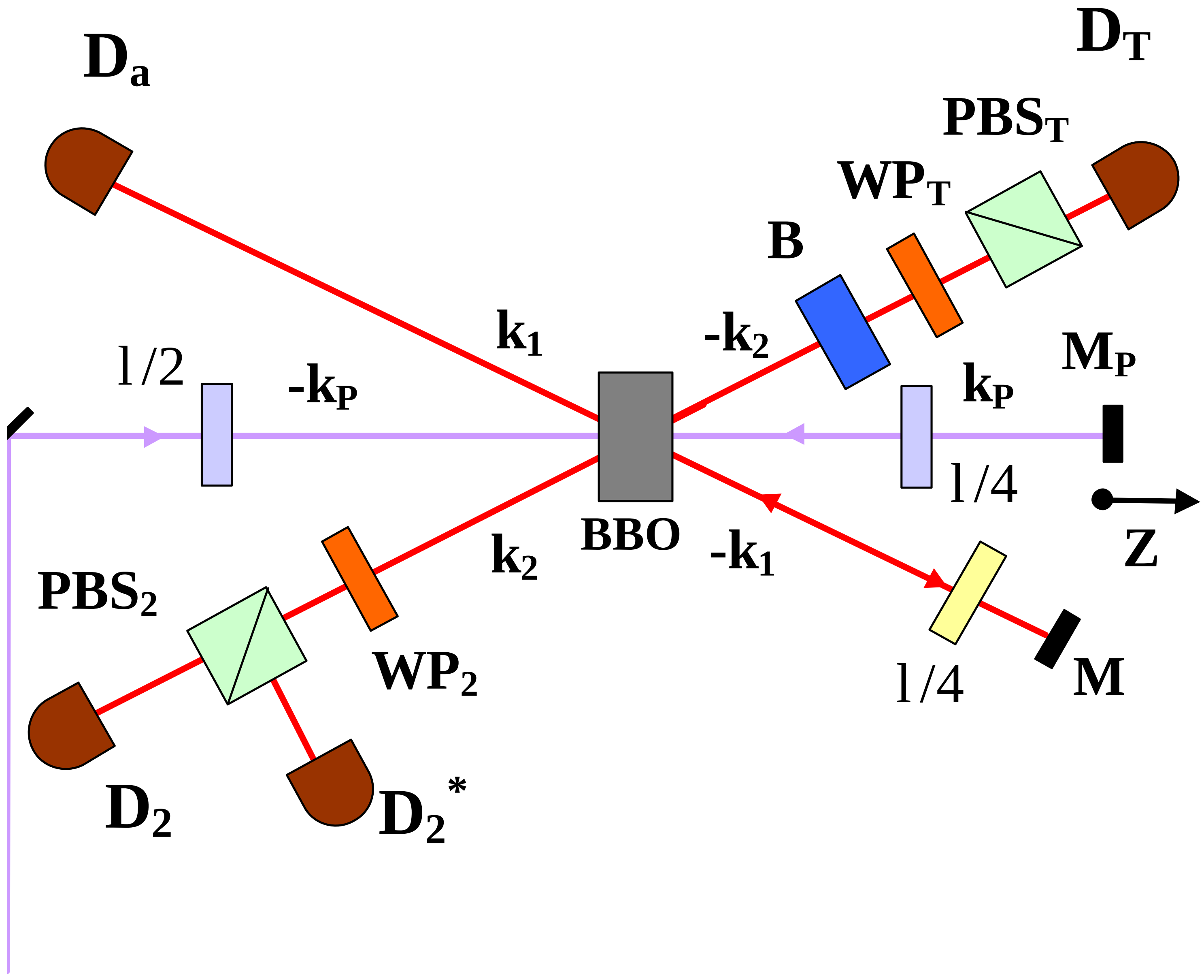

Figure 1
Experimental layout

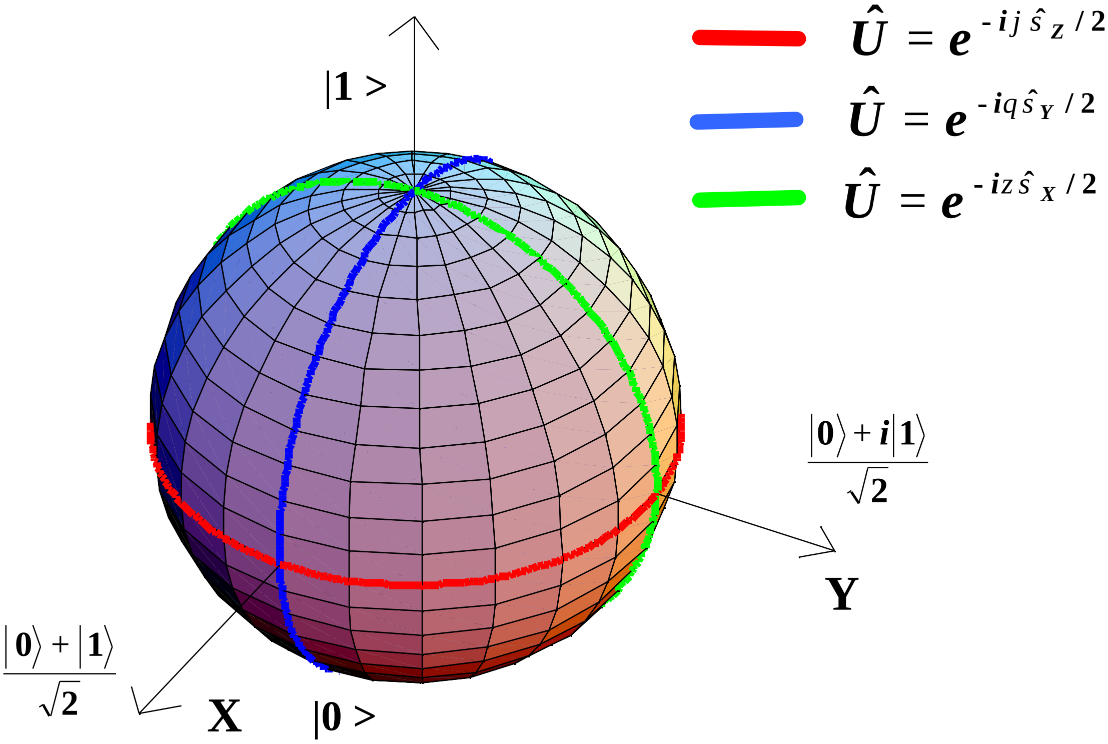

Figure 2
Transformations on the Bloch sphere

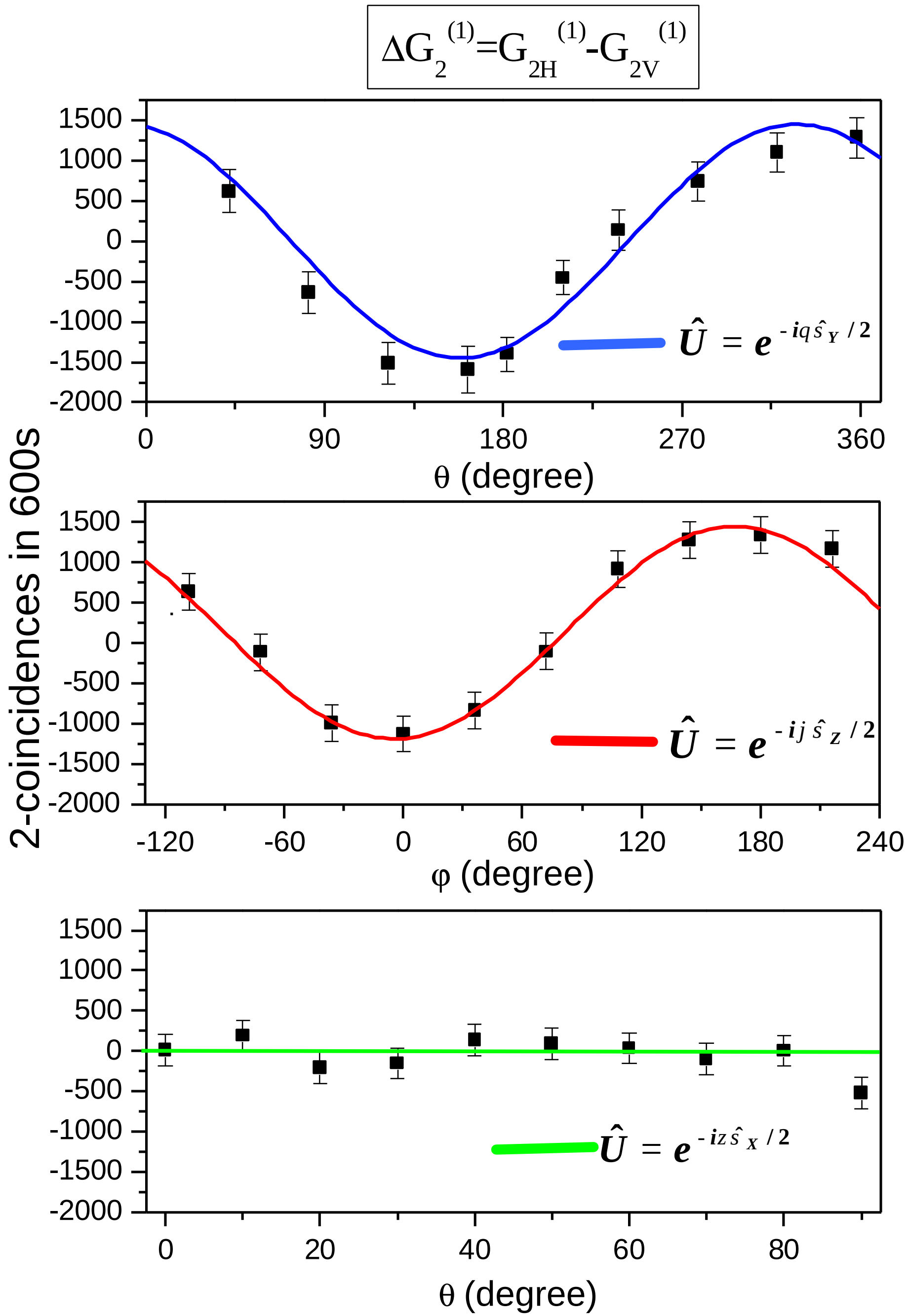

Figure 3
Low gain OPA

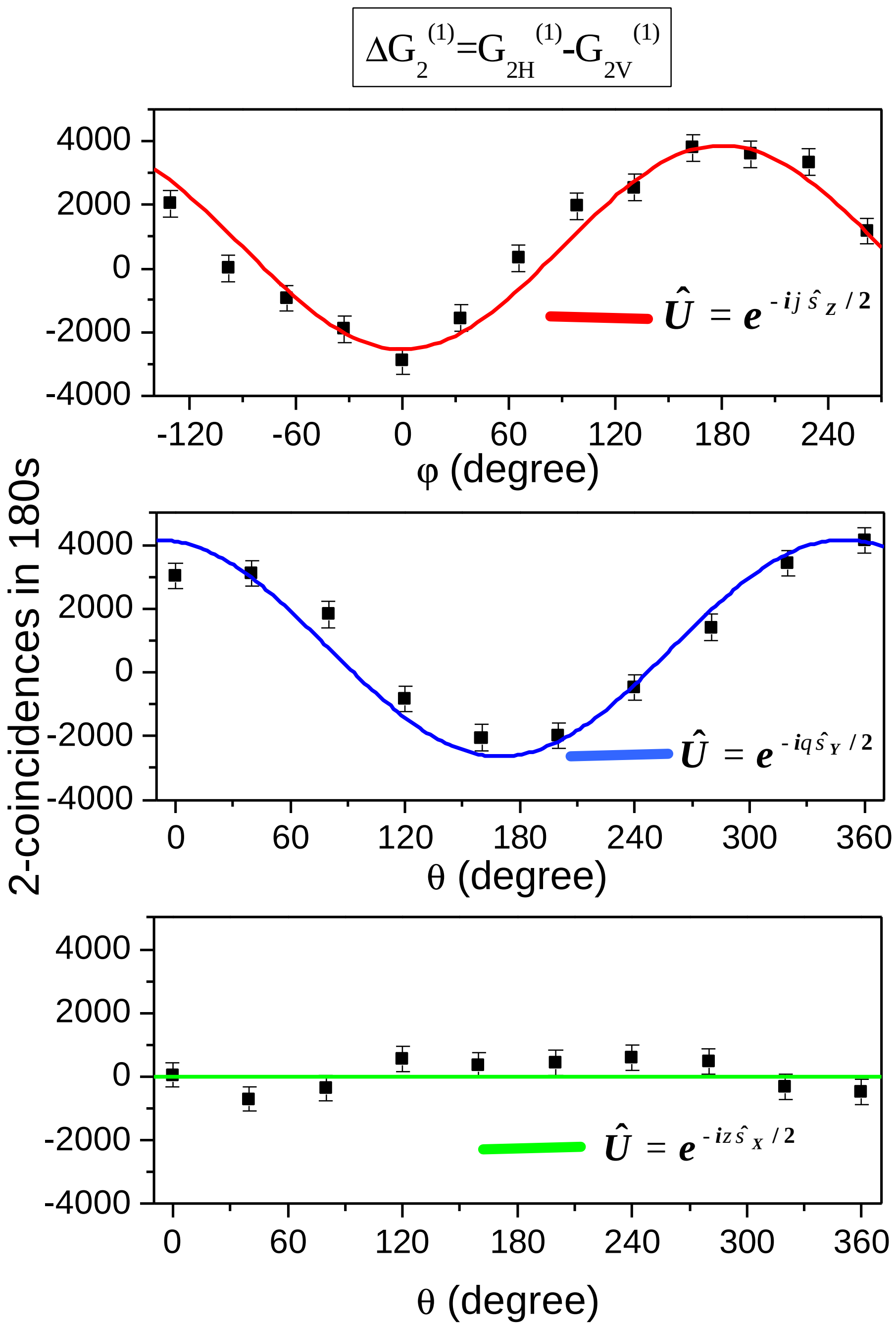

Figure 4
High gain OPA