

Photonic like Cooper Pairs

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Photons are the elementary particles carrying light. Contrary to electrons, which carry electric current, photons do not interact with each other in vacuum. However, when propagating in a material, for example water, photon pairs may effectively interact through the medium. For example, in Raman processes[1], an incident photon is typically converted into a lower frequency one, the remaining energy being converted into a vibration of the illuminated material. This is called a Stokes process. Another possibility is that the incoming photon absorbs a vibration and is converted into a blue-shifted (anti-Stokes) one. Since the first process may happen spontaneously while the second requires population in the vibrational degree of freedom, Stokes processes are much more likely than anti-Stokes, at least in low temperatures, where low is to be understood regarding the vibrational energy.

Sometimes, these processes can combine into a single scattering event in which the vibration created by a Stokes conversion is the one that generates an anti-Stokes photon. While such a combined Stokes–anti-Stokes process is often obfuscated by the usual single scattering mechanisms, this second-order effect dominates the anti-Stokes production in the absence of native thermal quanta of vibration [2, 3]. In this case, both events can be understood as a single energy preserving scattering process in which two incoming photons of frequency ω_L effectively interact through the medium to generate a pair of outgoing photons, one red and one blue-shifted from the incident light. This phenomenon has been observed in materials as diverse as diamond and water[4], and should be present as long as Raman resonances are available.

In this work [5] we demonstrate theoretically and experimentally that photon pairs may also interact via a virtual vibration, meaning that the energy exchanged in the process is outside the spectral energy range of normal vibrations in the medium. In this case, the interaction is mediated by the vacuum of the quantized vibrational degree of freedom and the output field is composed of twin photons of different tunable frequencies.

The same process occurs for electrons in a metal at very low temperatures, where virtual vibrations of the medium attractively couple them, forming the so-called Cooper pairs. In fact, the Hamiltonian derived in our work is the bosonic counterpart of the standard BSC Hamiltonian in the mean field approximation. For electrons, this phenomenon changes a normal metal into a superconductor. Cooper pairs are the supercurrent carriers and we have shown here their photonic counterparts. Whether this analogy can be extended to a photonic equivalent of superconductivity is a challenging and intriguing question for future investigation.

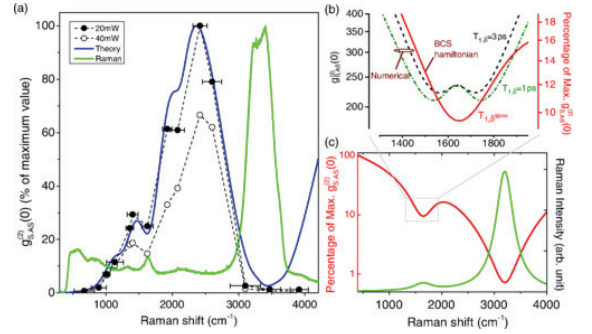


Figure 1: SaS correlation function $g^2(0)$ for different values of Raman shifts. (a) Experimental values are shown as symbols connected by dashed lines, at two excitation laser powers (see the legend). The green solid line represents the Raman spectrum of water. The solid blue line is the correlation calculated within a perturbative BCS approach [Eq. (3) of Ref(5)], using as input the experimental Raman spectrum, without fitting parameters. (b),(c) The correlation function $g(2)S,AS(0)$ is calculated (solid red line) within a perturbative BCS approach for a simplified model with only two vibrational modes of the water molecule [green line in (c)], shown near the real scattering condition ($k=q$)1640 cm^{-1} . We also present as dashed and dash-dotted lines the numerical solutions to the problem of a single vibrational mode, including two values for the vibrational relaxation time T_1 .

- [1] Raman, C. V. & Krishnan, K. S. A New Type of Secondary Radiation. *Nature* **121**, 501–502 (1928).
- [2] Klyshko, D. N. Correlation between the Stokes and anti-Stokes components in inelastic scattering of light. *Sov.J.Quantum Electron.* **7**, 755–760 (1977).
- [3] Parra-Murillo, C. A., Santos, M. F., Monken, C. H. & Jorio, A. Stokes-anti-Stokes correlation in the inelastic scattering of light by matter and generalization of the Bose-Einstein population function. *Phys. Rev. B* **93**, 125141 (2016).
- [4] Kasperczyk, M. *et al.* Temporal Quantum Correlations in Inelastic Light Scattering from Water. *Phys.Rev.Lett.* **117**, 243603 (2016).
- [5] Saraiva, A. *et al* Photonic Counterparts of Cooper Pairs, *Phys. Rev. Lett.*, **119**, 193603 (2017)