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QUANTUM PLASMONICS

Mix and match

It has long been assumed that the quantum statistics of light are preserved when photons interact with plasmons. An analysis of the scattering process shows that this is not always the case, as light can mix and match different plasmonic pathways.

Mark Tame

There has been immense interest in plasmonic systems owing to their ability to miniaturize optical devices down to the nanoscale for applications in sensing, communication and information processing[1,2]. The key feature of plasmonic systems is that they utilize nanostructures made from a combination of dielectric and metal to support electromagnetic excitations called surface plasmon polaritons (SPPs), which are accompanied by highly confined fields. Over the past two decades, plasmonics has begun to focus on the study of quantum effects[3] and how to use plasmonic systems to build compact quantum devices[4]. It is generally assumed that SPPs preserve the statistics of the light field used to excite them. This well-accepted tenet of quantum plasmonics has been verified in numerous scenarios, and researchers have relied on it to develop a wide array of plasmonic quantum devices. Now, writing in *Nature Communications*, Chenglong You and colleagues[5] report that the quantum statistics of light are not always preserved in plasmonic systems.

The preservation of the quantum statistics is based on a number of key assumptions, including that SPPs are bosons just like photons, so that the coupling between SPPs and photons at the quantum level is linear[6]. As a result, multiphoton states can simply be transferred — or converted — into SPPs and vice versa. Another key assumption is that there are no significant scattering effects present during the conversion process — it is this fundamental assumption that You and collaborators tested in their work. When they took coherent and incoherent bosonic scattering in a plasmonic system into account, the quantum statistics of a multiparticle light field were not preserved during the conversion process.

You and collaborators investigated the modification of the quantum statistics of multiparticle states of light owing to both indistinguishable (coherent) and distinguishable (incoherent) bosonic scattering processes occurring during the conversion of photons to SPPs, and back to photons again. Essentially, the coherent scattering processes in plasmonic structures can lead to different interference pathways for the photons (Fig. 1a) and these may be controlled by the relative coupling to the confined plasmonic near field. This near-field coupling determines the probability for a photon to travel along a given path and experience a particular phase kick, setting up different phase conditions for the resulting multiparticle dynamics. Combined with incoherent scattering, this coherent scattering modifies the quantum statistics of light.

It is fascinating that these scattering processes are fundamentally different to the coherent interactions previously observed in quantum plasmonic systems. For example, in Hong–Ou–Mandel bosonic interference with two indistinguishable SPPs[7,8], interference of purely coherent processes involving two plasmons modifies the two-photon statistics, whereas both coherent and incoherent scattering contribute to the process observed by You and collaborators.

To demonstrate the concept, the team used a plasmonic structure comprising a gold film with two slits. By focusing a laser onto a rotating ground glass plate, they produced a pseudo-thermal state of light consisting of multiple photons, with which they illuminated one of the slits to excite the plasmonic system.

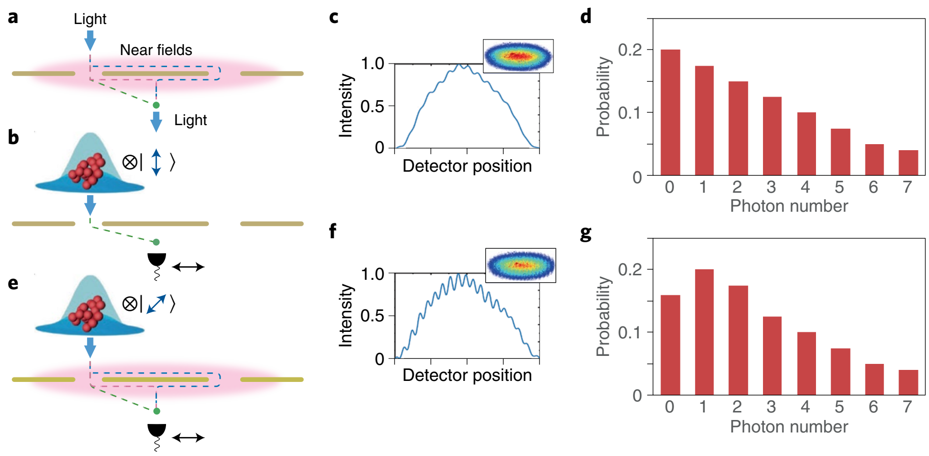

Fig. 1 | The quantum statistics of light interacting with the near fields of a two-slit plasmonic system are not preserved. a, Different interference pathways of light, each controlled by the relative coupling to the confined near field that supports them. The pathways give different phase kicks. **b**, A vertically polarized multiparticle thermal state of light does not couple to any plasmonic near fields due to mode-matching conditions and follows a direct pathway through the slit. **c**, A detector monitoring the field below the plasmonic system shows no spatial interference in the intensity profile (inset shows the 2D intensity profile). **d**, The thermal statistics in the photon number are preserved. **e**, A diagonally polarized thermal state of light has a component of horizontal polarization, allowing the light to partially couple to plasmonic near fields on the top and bottom surfaces of the gold film. The horizontal component can thus traverse near-field paths with different phases compared with the vertical component. **f**, Spatial interference in the intensity profile resulting from the coherent interaction between direct and near-field paths (inset shows the 2D intensity profile). **g**, A subthermal distribution in the photon number indicates that the quantum statistics are not preserved. Figure adapted from ref. [5] under a Creative Commons licence CC BY 4.0 (http://creativecommons.org/licenses/by/4.0/).

When the thermal state of light is vertically polarized (Fig. 1b), it does not couple to any SPPs and follows a direct scattering pathway through the slit. The resulting state shows no spatial interference in the intensity profile (Fig. 1c), and the thermal statistics of the photon number are preserved (Fig. 1d).

A diagonally polarized state of light (Fig. 1e), however, is a superposition of vertical and horizontal polarization. And the horizontal component allows a partial coupling of the light to SPPs on the top and bottom surfaces of the gold film, opening additional scattering pathways. The ratio of horizontal polarization relative to vertical polarization in the input state determines the relative probabilities of light propagating along the surfaces. As a result, the horizontal component of the diagonally polarized state displays spatial interference in the intensity profile, as the different paths coherently interact with each other (Fig. 1f).

The overall combination of incoherent and coherent scattering, or more precisely of vertical light from a direct pathway with no spatial interference and horizontal light from direct and indirect pathways with spatial interference, is accompanied by a modification in the photon number statistics, leading to a subthermal distribution resembling that of a coherent state (Fig. 1g). This photon–SPP–photon transmission process does not preserve the quantum statistics.

But is this a special case or is the phenomenon more general? To answer this question, You and collaborators considered a more complex system comprising two sources of multiparticle thermal light, each illuminating one of the two slits in the gold film. In this setting, two thermal states interacted with the plasmonic system, which converted them into one subthermal state of light — confirming that the quantum statistics are not preserved.

The results by You and collaborators are an important step forward in the development of plasmonic systems for manipulating coherence and quantum statistics. Although similar effects have been studied in nonlinear optics, photonic lattices and Bose–Einstein condensates, this is the first time it has been observed using optical near fields due to SPPs. Apart from triggering a reassessment of previous results in quantum plasmonics research, the finding opens up some intriguing new opportunities for control in quantum plasmonic devices by exploiting coherent and incoherent scattering processes. Future work utilizing this deterministic multiparticle interference effect, for example, with localized surface plasmons in nanostructures and metamaterials, may lead to novel quantum sensing and imaging applications[1,4]. The controlled thermalization and anti-thermalization of light fields may also provide a test-bed for quantum thermodynamic effects[9] and statistically disordered systems[10], and lead to the design of efficient photovoltaic devices for the capture and control of energy[11].

Furthermore, incoherent and coherent scattering in the context of light–matter interactions is an exciting idea. For example, plasmonic structures combined with emitters can produce quantum states of light. Exploiting interactions of different pathways of multiparticle plasmonic near fields with emitters may open up fundamentally new ways to design and control photon sources. ❐

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Published online: 26 October 2021
https://doi.org/10.1038/s41567-021-01399-6

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Competing interests

The author declares no competing interests.