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Creation of single-photon entangled states around rotating black holes

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HIGHLIGHTS

- Kerr black holes rotate the polarization angle and imprint OAM to X-ray photons emitted by the accretion disk.
- Polarization and OAM are two degrees of freedom of single-photons that encode two qubit of quantum information.
- The X-ray photons emitted in the transition region of the disk manifest entangled states of polarization and OAM.
- The degree of entanglement depends on the speed the black hole is spinning.
- Maximally entangled states of X-ray photons should be observed for maximally rotating black holes.

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ABSTRACT

Recently, numerical simulations showed that X-ray photons emitted by accretion disks acquire rotation of polarization angle and orbital angular momentum due to strong gravitational field in the vicinity of the rotating black holes. Based on these two degrees of freedom we construct a bipartite two-level quantum system of the accretion disks photons. To characterize the quantum states of this composite system we consider linear entropy for the reduced density matrix of polarization with the intention to exploit its direct relation with the photons degree of polarization. Accordingly, the minimum degree of polarization of X-ray radiation located in the transition region of the accretion disk indicates a high value of the linear entropy for the photons emitted on this region, inferring a high degree of entanglement in the composite system. We emphasize that for an extreme rotating black hole in the thermal state, the photons with energies at the thermal peak are maximally entangled in polarization and orbital angular momentum, leading to the creation of all four Bell states. Detection and measurement of quantum information encoded in photons emitted in the accretion disk around rotating black holes may be performed by actual quantum information technology.

1. Introduction

Rotating black holes (RBH) are among the most mysterious predictions general relativity has made. Spinning black holes not only curve the space-time, as in the case of Schwarzschild black holes, but also strongly twist the surrounding space-time. The curvature and twisting of space-time nearby rotating black holes influence the photons emitted by the accretion disk. The strong gravitational field in the vicinity of spinning BH rotates the angle of polarization and imprint orbital angular momentum (OAM) to X-ray photons emitted by the accretion disk.

The efforts to unveil some undetermined characteristics of rotating black holes, such as the spin, were mainly focused in the recent years over detecting the polarization of X-ray radiation coming from the accretion disk. It was pointed out in Schnittman and Krolik (2009), Chandrasekhar (1960), Connors and Stark (1977), Connors et al. (1980), Cunningham (1976), Agol and Krolik (2000) and Krawczynski (2012), based on Stokes parameters calculation, that photons emitted by the accretion disk of black holes in the thermal state, should possess linear polarization, either parallel or perpendicular to the plane of the disk. Thus, on the outer region of the disk, at low energies, the X-ray radiation is horizontally polarized, parallel to the plane of the disk. The polarization angle of photons coming from the innermost region is shifted through vertical polarization, perpendicular to the disk plane due to the strong gravitational field in the vicinity of the RBH. The degree of polarization is higher in these two regions of the accretion disk. Between the outer and inner regions of the disk, at the transition region, the relative contributions of horizontal and vertical polarized photons are nearly equal and very low polarization is observed. The transition region is characterized by very low degrees of polarization that tends to zero for extreme spinning black holes (Schnittman and Krolik, 2009; Krawczynski, 2012).

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On the other hand, numerical simulations (Harwit, 2003; Tamburini et al., 2011; Yang and Casals, 2014; Elias, 2008; Uribe-Patarroyo et al., 2011), suggest that strong dragging frame effect near rotating black holes imprint nontrivial orbital angular momentum (OAM) modes to photons emitted by the accretion disk. X-ray photons coming from the disk are forced by the twisted space-time around spinning black holes to acquire OAM. As the BH spins faster the OAM spectrum extend to wider values carrying both positive and negative OAM ($\pm \ell$).

When measured by a distant observer, the X-ray radiation coming from accretion disk should carry linear polarization (horizontal or vertical) and specific (positive or negative) OAM values as consequence of strong general relativistic effects that occur in the presence of the rotating black holes. We further develop the analysis of radiation emitted near RBH considering here the polarization and OAM modes as two degrees of freedom that can fully specify the states of the accretion disk's X-ray photons.

Generically, the states of X-ray photons emitted near rotating black holes should be determined by constructing the 4×4 density matrix (McMaster, 1954; 1961), of the composite system consisting of polarization and OAM modes, as two distinct subsystems. In order to avoid the complications that arise in constructing this bipartite system density matrix we focus our attention over the reduced density matrix of polarization subsystem, which is easy inferred from Stokes parameters. Our main assumption here is that the degree of mixedness of one subsystem determines the degree of entanglement of the composite system, (Gamel and James, 2012; Perumangatt et al., 2015b; Horodecki et al., 2009; Bjork et al., 2014; Genoni et al., 2008; Wei et al., 2005). Moreover, a high degree of mixedness present in the polarization subsystem suggests a high degree of non-separability (entanglement) of the composite system.

We consider the linear entropy of the X-ray photons polarization in order to shed light on the degree of mixedness in this subsystem. The decision to choose here the linear entropy as the measure of the degree of mixedness of the polarization subsystem was inspired by its relation to the degree of polarization.

The linear entropy values vary from low levels in the outer and the innermost regions of accretion disk of rotating black holes, regions characterized by a high degree of polarization, to very high levels at the transition region where a very low degree of polarization is encountered. Based on the linear entropy values we conclude that at the composite system level, the photons at the outer and innermost regions of the disk are characterized by high degrees of separability, while the X-ray originated in the transition region are endowed with a high degree of nonseparability (entanglement).

The degree of entanglement of X-ray photons in the transition region is influenced (via the degree of polarization) by the speed of BH rotation. Broadly, the faster the BH spins the higher the degree of entanglement of X-ray photons in polarization and OAM. Under these circumstances, it is expected that the maximally entangled states to appear in the case of an extremal RBH ($a = 1$), for the photons at the energy peak in the transition region.

The maximal entanglement in polarization and OAM of X-ray photons coming from the transition region of the accretion disk is expressed via Schmidt decomposition (Bergou and Hillery, 2013; Ekert and Knight, 1995), by the all four Bell states.

An indirect probe of the entangled states of the X-ray radiation from accreting black holes may come from the forthcoming space missions, the Imaging X-ray Polarimetry Explorer (IXPE) by NASA, (Weisskopf, 2016) and the X-ray Imaging Polarimetry Explorer (XIPE) by ESA, (Soffitta et al., 2013; Soffitta, 2016). The scope of these missions is to explore the degree and angle of polarization on basically all classes of X-ray astronomical sources, from neutron stars and stellar-mass black holes, to supernova remnants and to active galactic nuclei (AGN). The detection of a minimum degree of polarization situated in the transition region of the accretion disk is a good indication of the presence of entangled states encoded in X-ray photons.

However, the final proof of entangled states of X-ray photons emitted by accretion disks is the direct measurement. The entangled states of X-ray photons can be measured by quantum optics setups (Khoury and Milman, 2011; Perumangatt et al., 2015a; Mair et al., 2001; Krenn, 2014), with the limitation imposed here by the high energy of photons (X-ray band). With the later progress in technology related to X-ray laboratory research (Gunst, 2016; Sasaki and McNulty, 2008; Peele, 2004; Shwartz and Harris, 2011), leading to quantum computation with X-ray photons (Gunst, 2016) legitimate hopes are directed towards detection and measurements of the Bell states the X-ray radiation coming from galactic active nuclei and solar-mass black holes accretion disk.

Our present work adds a quantum information component to the X-ray astronomy that may prove to be important in the light of today flourishing development of quantum technologies. Processing the quantum information coming from accreting black holes is expected to encompass valuable information on the link between general relativity and quantum theory near these spectacular astrophysical bodies. Astronomy equipped with quantum information instruments certainly will play the crucial role in observing quantum gravity effects.

2. X-ray polarization from accreting black holes

Expectations to unveil some of the black holes undetermined characteristics, such as the spin, are related to measuring the polarization of X-ray photons emitted by the accretion disk. In analyzing the polarization of radiation emitted by the accretion disk in thermal state we consider the simplest model of a geometrically thin, optically thick, steady-state accretion disk, aligned with the BH spin axis.

Stokes parameters are central in attempts (Schnittman and Krolik, 2009; Chandrasekhar, 1960; Connors and Stark, 1977; Connors et al., 1980; Cunningham, 1976; Agol and Krolik, 2000; Krawczynski, 2012) to estimate the degree of polarization and the polarization angle of X-ray radiation emitted by accretion disk, the two parameters that quotes the characteristics of black holes. Considering that the polarization of X-ray photons is induced by Compton scattering, which prevent the circular polarization, the Stokes parameters are:

$$s_0 = I \tag{1}$$

$$s_1 = Q = I cos 2\chi \tag{2}$$

$$s_2 = U = I sin 2\chi , \tag{3}$$

where χ is the polarization angle.

The angle of polarization and the degree of polarization, are derived from the Stokes parameter in the following manner :

$$tan 2\chi = \frac{U}{Q} \tag{4}$$

and

$$\delta = \sqrt{Q^2 + U^2}, \tag{5}$$

respectively.

These two parameters are sensitive to the black hole spin (a).

Recent numerical simulations (Schnittman and Krolik, 2009; Krawczynski, 2012) scaled up the dependency of the degree of polarization and the angle of polarization by the spin parameter of rotating black holes. It was shown that X-rays emitted near the