Generation and detection of x-ray entanglement

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The creation and detection of non-classical and entangled quantum states of x-ray light by coherent control of nuclear dynamics will be discussed. After a introduction and motivation of x-ray entanglement, coherent control by magnetic field switching as well as the generation and detection of x-ray entanglement will be addressed. Finally, possible future directions will be suggested.

X-ray entanglement

Non-classical and entangled states are an intrinsic and characteristic feature of quantum mechanics, and therefore could clearly demonstrate the advancement of x-ray science to the quantum realm. In the optical domain, already today they admit far-fetching applications such as measurements beyond classical limits, and at the same time provide an experimental access to the foundations of quantum mechanics. The abstract vision is to develop techniques to make use of non-classical states to improve preparation, control and detection in x-ray science. A particular case of entanglement suitable for experiments in the low-excitation regime is single-particle entanglement [1]. For example, a single photon can entangle two field modes A and B as

$$|\Psi\rangle = \alpha\,|1\rangle_A|0\rangle_B + \beta\,|0\rangle_A|1\rangle_B \qquad \text{where} \qquad |\alpha|^2 + |\beta|^2 = 1\,. \tag{1}$$

It is important to note that it is not the photon that is entangled, but rather the two field modes A and B which are entangled by the distribution of a single excitation over the two modes.

Coherent control of nuclear forward scattering

Coherent control of nuclear excitations has been a long-time goal, as it is related to a number of promising applications such as nuclear quantum optics, isomer triggering or nuclear lasers. Ref. [2] reported suppression of the coherent decay of nuclear excited states in nuclear forward scattering (NFS) by switching the direction of the hyperfine magnetic field in the nuclear target. After the coherent excitation, the change of quantization axis via the magnetic field switching projects the excited nuclei into a new state basis. The coherent decay is then suppressed, since the de-excitation amplitudes of the new basis states destructively interfere. Switching back the magnetic field direction at a suitable later time then leads to a sudden emission of the coherently stored excitation. Since the physical mechanisms underlying the suppression of the coherent decay are analogous to well-known coherence phenomena in atomic quantum optics such as electromagnetically induced transparency, magnetic switching offers a direct route towards nuclear quantum optics.

Generation of x-ray entanglement

It was shown in [3, 4] that generalizing the magnetic switching setup in [2] could allow to achieve 14.4 keV single-photon entanglement in NFS. The coherent scattering of the synchrotron radiation (SR) pump pulse can be controlled by a sequence of magnetic field switchings such that two coherent decay pulses with different photon polarizations are emitted. Depending on the switching sequence, the two pulses can be emitted either time-resolved or overlapping in time. Since the SR pulse typically creates only at most one (and more often no) nuclear resonant excitation in the target, only one photon will be emitted in either of the two field modes, with no way of knowing in which one. This lack of knowledge leads to the entanglement of the two modes as in Eq. (1). In a proof-of-principle experiment, the entangled signal could be separated from the background using time gating. More advanced setups could apply x-ray polarizers and piezoelectric fast steering mirrors to spatially separate the entangled signal from the background. Alternative methods to produce entangled states without magnetic switching include NFS in Faraday geometry or NFS followed by x-ray beam splitters as in the optical frequency range.

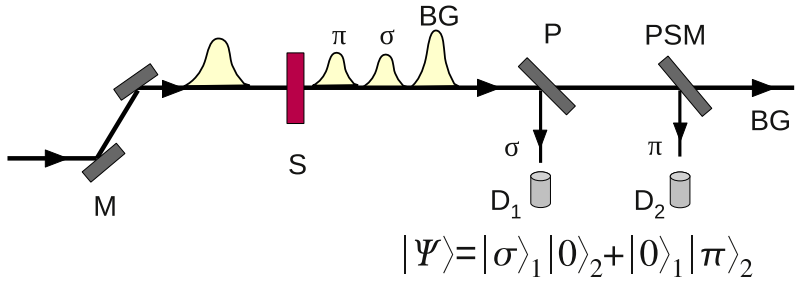

Figure 1: Generation of the single-photon entangled state $|\Psi\rangle$. The SR pulse is monochromatized (M) before it reaches the sample (S). The coherently scatted radiation is separated into three pulses: the background (BG) emitted immediately after the SR pulse, and the delayed entangled σ-polarized and π-polarized pulses, which can be separated from the forward response by the polarizer (P) and the piezoelectric fast steering mirror (PSM), respectively.

Detection of x-ray entanglement

In contrast to atomic quantum optics, state-of-the-art NFS experiments essentially operate in the single-photon regime and do not offer auxiliary local oscillator fields in phase with the scattered light. These limitations preclude part of the detection schemes suggested or experimentally demonstrated in the optical regime. However, a suitable setup was proposed in [5]. It essentially relies on an interferometer setup, with a splitting of the two single-photon entangled modes, followed by a subsequent recombination of the two modes on a beam splitter and correlation measurements on the two beam splitter output ports. By monitoring the correlation signal in dependence on phase shifts applied to the two beams separated in the interferometer, a Bell inequality can be violated, thereby verifying the entanglement. The most straightforward implementation would rely on background removal by time gating and an input state of temporally overlapping entangled modes with different polarization, such that the two pulses arrive simultaneously at the detectors for the correlation measurement. A different approach to verify the presence of entanglement is to implement a quantum protocol relying on entanglement, such as quantum state teleportation [5]. Experimentally, however, this is more challenging than the violation of Bell inequalities, as in addition to the entangled photon state the simultaneous presence of a photonic signal state to be teleported as well as more advanced correlation measurements are required.

Future prospects

Possible future directions could be the development of a true x-ray single photon source, the creation and detection of two-photon entanglement via down-conversion, the extraction of the entangled state from the background using x-ray optics, the implementation of quantum algorithms such as teleportation, cryptography or key distribution, and the implementation of quantum-assisted measurement schemes in the x-ray range.

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