Quantum correlations in the two-photon decay of few-electron ions

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Synopsis The photon-photon polarization entanglement in the two-photon decay of metastable ionic states has been analyzed in the framework of the density matrix and second-order perturbation theory. Emphasis is placed especially upon the relativistic and non-dipole effects along the hydrogen- and helium-isoelectronic sequence.

Studies on the two-photon transitions of few-electron atoms and ions have a long tradition since Maria Göppert-Mayer’s pioneering work in the 1930’s. While the focus of most earlier investigations was placed upon the two-photon decay of light systems, some recent interest was shifted towards the high-Z domain. For example, a series of experiments have been carried out at the GSI storage ring during the last years in order to explore the two-photon decay of helium-like uranium \(^{90}\text{U}\)^{2+} ions [1]. Up to the present, however, these experiments have been restricted to the total and energy-differential rates. It is only very recently that angular and polarization correlation measurements have become realistic for x-ray photons due to the advances in detector technology, and which may provide information about relativistic, many-body and parity non-conservation phenomena in heavy ions [2].

![Figure 1](image-url) Concurrence of two photons in full relativistic theory (black) and dipole approximation (blue).

In this contribution, we analyze and discuss the quantum correlations between the polarization states of the photons emitted in the (two-photon) decay of helium-like ions. Based on relativistic, second-order perturbation and density matrix theory, detailed calculations have been performed for the degree of entanglement (in terms of the concurrence measure \(C\)) for the 1s\(^2\)p\(^+\)1\(^1\)S\(_0\) → 1s\(^2\)\(^1\)S\(_0\) and 1s\(^2\)p\(^+\)p\(^+\)1\(^1\)S\(_0\) two-photon transitions [3]. For example, Fig. 1 displays for both transitions the predicted concurrence as function of the opening angle between the photons. Results are shown for the energy sharing (parameter) \(y = E_\gamma_1/(E_\gamma_1 + E_\gamma_2) = 1/4\).

As seen from the figure, the (degree of) quantum correlations appear very sensitive to the decay geometry. In particular, our calculations show that the concurrence of two photons emitted in the 1s\(^2\)p\(^+\)1\(^1\)S\(_0\) decay vanishes at the opening angle \(\theta = \pi/2\), while it is maximal for the parallel (\(\theta = 0\)) and back-to-back (\(\theta = \pi\)) photon emission. This behaviour can be well understood from the conservation of the projection of the total angular momentum of the overall system “ion + two photons”. For \(\theta = 0\) and \(\pi\), for example, such a conservation law, together with the spherical symmetry of the initial and final ionic state, immediately implies maximally entangled Bell (linear polarization) states \(|\Psi_{\theta=0}\rangle = |yy\rangle + |xx\rangle\) and \(|\Psi_{\theta=\pi}\rangle = |yy\rangle - |xx\rangle\) and, hence, maximal degree of entanglement, \(C = 1\).

A qualitatively similar behaviour of the concurrence measure can be observed also for the 1s\(^2\)p\(^+\)p\(^+\)1\(^1\)S\(_0\) two-photon transition. However, in contrast to the decay of \(^1\)S\(_0\) state, the degree of entanglement is then not symmetric anymore with respect to the opening angle \(\theta = \pi/2\) as caused due to the interference between the possible decay channels (see right panel of Fig. 1).

References

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