

Single-atom-catalysts (SACs) aim at bridging the gap between homogeneous and heterogeneous catalysis, offering ultimate atom economy and turning every active site accessible, like homogeneous catalysts but adding recyclability. Major challenges in the field encompass the development of materials with precise functionalities for robust metal ion binding and metal cooperativity in heterometallic and mixed valence SACs. Meeting the first challenge could facilitate higher metal contents avoiding clustering and leaching upon reaction and catalyst recycling. This is also a prerequisite for the second challenge (metal-metal cooperation), since low metal content translates into large intermetallic distances. Here-in, we designed a two-dimensional mixed-valence ionic copper catalyst employing an out of plane functionalized graphene with nitrile groups (cyanographene) for the robust coordination of Cu(II) ions, which were partially reduced to Cu(I) due to graphene-induced charge-transfer. STEM analysis, EPR spectroscopy and EXAFS verified the truly single atom character of the material. Inspired by nature's selection of Cu(I) in enzymes for oxygen activation, this two-dimensional mixed-valence SAC was challenged in two O₂-mediated reactions: the oxidative coupling of amines and the oxidation of benzylic C-H bonds towards high-value pharmaceutical synthons. High conversions (up to 98%), selectivities (up to 99%), and recyclability were attained with very low metal loadings in the reaction. The synergistic effect of Cu(II) and Cu(I) was the essential part in the reaction mechanism forming a cyclic intermediate state with the reactants, as suggested both by theoretical calculations and experimental results.