Direct phase-sensitive identification of a *d*-form factor density wave in underdoped cuprates

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PHYSICS

The identity of the fundamental broken symmetry (if any) in the underdoped cuprates is unresolved. However, evidence has been accumulating that this state may be an unconventional density wave. Here we carry out site-specific measurements within each CuO_2 unit cell, segregating the results into three separate electronic structure images containing only the Cu sites [*Cu*(*r*)] and only the *x*/*y* axis O sites [$O_x(r)$ and $O_y(r)$]. Phase-resolved Fourier analysis reveals directly that the modulations in the $O_x(r)$ and $O_y(r)$ sublattice images consistently exhibit a relative phase of π. We confirm this discovery on two highly distinct cuprate compounds, ruling out tunnel matrix-element and materials-specific systematics. These observations demonstrate by direct sublattice phase-resolved visualization that the density wave found in underdoped cuprates consists of modulations of the intraunit-cell states that exhibit a predominantly *d*-symmetry form factor.

broken symmetries weaken simultaneously with increasing p and disappear jointly near $p_c = 0.19$ (13). For multiple cuprate compounds, neutron scattering reveals clear intraunit-cell breaking of rotational symmetry (14, 15, 16). Thermal transport studies (17) can likewise be interpreted. Polarized X-ray scattering studies reveal the electronic inequivalence between O_x and O_y sites (18) and that angular dependent scattering is best modeled by spatially modulating their inequivalence with a *d*-symmetry form factor (19). Thus, evidence from a variety of techniques indicates that $\boldsymbol{Q} = 0$ C_4 breaking (electronic inequivalence of O_x and O_y) is a key element of underdoped-cuprate electronic structure. The apparently distinct phenomenology of $\boldsymbol{Q} \neq 0$ incommensurate density waves (DW) in underdoped cuprates has also been reported extensively (20–27). Moreover, recent studies (28, 29) have demonstrated beautifully that the density modulations first visualized by scanning tunneling microscopy (STM) imaging (30) are in-