The evolution of Sr$_2$IrO$_4$ upon carrier doping has been a subject of intense interest, due to its similarities to the parent cuprates, yet the intrinsic behaviour of Sr$_2$IrO$_4$ upon hole doping remains enigmatic. Here, we synthesize and investigate hole-doped Sr$_{2-x}$K$_x$IrO$_4$ utilizing a combination of reactive oxide molecular-beam epitaxy, substitutional diffusion and in-situ angle-resolved photoemission spectroscopy. Upon hole doping, we observe the formation of a coherent, two-band Fermi surface, consisting of both hole pockets centred at ($\pi$, 0) and electron pockets centred at ($\pi$/2, $\pi$/2). In particular, the strong similarities between the Fermi surface topology and quasiparticle band structure of hole- and electron-doped Sr$_2$IrO$_4$ are striking given the different internal structure of doped electrons versus holes.
The spin–orbit-coupled Mott insulator Sr$_2$IrO$_4$ exhibits a fascinating interplay between numerous competing energy scales, including spin–orbit coupling (SOC), Coulomb repulsion ($U$), Hund’s coupling ($J_{H}$), and has thus been subject of much recent interest$^{1-3}$. Close similarities between Sr$_3$IrO$_4$ and the parent cuprate La$_2$CuO$_4$ have also led to theoretical proposals that hole- and electron-doped Sr$_2$IrO$_4$ could likewise exhibit unconventional superconductivity$^{4,5}$. To date, the majority of work has focused on the electron-doped side of the phase diagram with reports of a momentum-dependent pseudogap in Sr$_2$−$_3$La$_1$IrO$_4$ and a $d$-wave-like gap in surface K-doped Sr$_2$IrO$_4$.$^6$. These are both features associated with cuprates, although no direct signature of superconductivity has been conclusively identified. On the other hand, the behaviour of Sr$_3$IrO$_4$ upon hole doping is less clear, as the vast majority of studies have examined Sr$_2$Ir$_{1-x}$Rh$_x$O$_4$.$^{9-13}$ and Rh substitution introduces a number of complexities beyond the doping of holes. As Rh is introduced into the IrO$_2$ planes, it removes a local $J_{eff}=1/2$ moment, leading to pairs of Rh$^{3+}$ and Ir$^{4+}$ non-magnetic impurities$^{14}$, which is analogous to Zn or Ni substitution for Cu in cuprates$^{15,16}$. In cuprate superconductors, the preferred doping sites are those that are not part of the CuO$_2$ planes, e.g., the A-site of cuprates with formula $A_x$CuO$_y$ (A = Sr or Ba). The A-sites are preferred because of the lower disorder potential that they evoke compared with sites within the CuO$_2$ planes; by analogy with Sr$_3$IrO$_4$, it is likely similarly advantageous to minimize disorder by doping the Sr-site with an appropriate dopant rather than to dope the Ir-site with Rh. Furthermore, Rh substitution should also change the average strength of the SOC$^{11}$, a key ingredient in the formation of the low-energy electronic structure.

To reveal the intrinsic behaviour of Sr$_3$IrO$_4$ upon hole doping, it is thus desirable to investigate a system without the intertwined complexity caused by Rh substitution. In principle, substitution of a monovalent alkali (e.g., Na$^+$ or K$^+$) on the A-site for divalent Sr$^{2+}$ should result in hole doping without the additional complexities introduced by Rh substitution, similar to the hole doping of the cuprate Ca$_{2-x}$Na$_x$CuO$_2$Cl$_2$ by Na substitution.$^{17-19}$ This has been demonstrated in $A_x$-$K_y$IrO$_4$ (A = Sr, Ba) to preserve the long-range magnetic order at moderate amount of doping (up to $x \approx 0.055$)$^{20-22}$. At present, however, no detailed spectroscopic measurements of any kind have been reported for $A_x$-$K_y$IrO$_4$ presumably due to the difficulty in synthesizing high-quality bulk single crystals. To overcome this challenge, we employ a combination of reactive oxide molecular-beam epitaxy (MBE) to synthesize initially undoped Sr$_2$IrO$_4$(001) thin films, followed by a substitutional diffusion process$^{23,24}$, which allows us to substitute K for Sr. This approach circumvents the extremely high vapour pressure of KO$_2$ at typical growth temperatures ($=10^{-2}$ torr at 850 °C)$^{25}$, which would otherwise prevent the direct incorporation of K into the thin film; additional details about this process can be found in the Methods section. Afterwards, in-situ angle-resolved photoemission spectroscopy (ARPES) measurements of Sr$_{1.93}$K$_{0.07}$IrO$_4$ thin films allow us to disentangle, for the first time, the effects of hole doping from changes in the SOC, magnetic landscape, and strong disorder scattering in the layered iridates. In doing so, we reveal that upon hole doping, coherent quasiparticles emerge together with the collapse of the Mott gap, in contrast to what has previously been reported with Rh substitution.

**Results**

**Chemical potential shift with doping.** In principle, the addition of K into Sr$_3$IrO$_4$ can result in either hole or electron doping. If K does not replace Sr, either when adsorbed on the surface$^{6,5,26}$ or intercalated, this should result in electron doping. On the other hand, if K$^+$ substitutes for Sr$^{2+}$, this should result in hole doping. To conclusively demonstrate hole doping, we measured the shift in chemical potential $\Delta \mu$ between undoped, K surface-doped, and K-substituted samples. In Fig. 1a, we show representative energy distribution curves (EDCs) of the valence band from a single Sr$_2$IrO$_4$ sample when it is (i) initially undoped (black), (ii) following surface K-deposition (green), and finally (iii) after substitutional diffusion of K for Sr (purple). K surface deposition in step (ii) causes a shift of the spectra by $\Delta \mu = +0.5 \pm 0.1$ eV, consistent with electron doping as previously reported by Kim et al.$^{4,5}$. In contrast, following substitutional diffusion in step (iii), all features are shifted to lower binding energy by $\Delta \mu = -0.4 \pm 0.1$ eV, in the direction consistent with hole doping as established by Louat et al.$^{12}$ via Rh substitution. This process also results in a clear change in the K 3p core levels (Fig. 1b), as K is oxidized and substituted into the SrO layer. We excluded the possibility of hole doping via Sr vacancies$^{27}$, interstitial oxygen, or oxygen vacancies$^{28}$, by verifying that the post-growth annealing steps had no observable effect when the K-deposition step was omitted (see Supplementary Note 2).

**Evolution of low-energy electronic structure.** To investigate the effects of K substitution, in Fig. 2 we compare an isomer map of an undoped Sr$_2$IrO$_4$ film at 0.3 eV binding energy (sample exhibited no weight at $E_F$) with a Fermi surface map of the same sample following K substitution. The isomer map of undoped Sr$_2$IrO$_4$ in Fig. 2a closely resembles those reported for undoped bulk crystals of Sr$_2$IrO$_4$. In reality, when an electron is removed from Sr$_2$IrO$_4$ (e.g., by photoemission or hole doping) 5$d^4$ holes are introduced in the IrO$_2$ plane, where the low-energy excitations are in fact a non-magnetic singlet $J_{eff}=0$ and a magnetic triplet state $J_{eff}=1$ (as described by Pärschke et al.$^{35}$). To remain consistent with the existing iridate literature, these bands may be referred to as $J_{eff}=1/2$ and $J_{eff}=3/2$ bands, following the convention for the undoped 5$d^5$ configuration. Furthermore, an electron addition 5$d^5$ state is non-magnetic with no degrees of freedom, suggesting that electrons and holes may couple differently to the local magnetic environment. The top of the occupied $J_{eff}=1/2$ band is at $(\pi, 0)$ and $(0, \pi)$, and the top of the $J_{eff}=3/2$
band lies at (0,0) and (π, π), using the notation assuming an idealized, undistorted IrO2 square lattice, as has been customary in the literature. Upon hole doping, the Fermi surface of Sr2−xKxIrO4 is now clearly composed of small, elliptical electron pockets closed about (π/2, π/2) and larger square hole pockets centred about (π, 0) and (0, π). A measurement of the Luttinger volumes of these pockets indicates a hole doping of x = 0.07 ± 0.02, consistent with the observed shift in chemical potential, conclusively demonstrating hole doping via K substitution.

In Fig. 3a-d, we compare spectra from undoped Sr2IrO4 and Sr2−xKxIrO4 along both the (0,0)−(0,π) and (π/2,0)−(π/2,π) momentum cuts. For undoped Sr2IrO4, the broad but distinct Ieff = 1/2 band reaches its maximum at (0,π) as reported previously in bulk single crystals, whereas for Sr1.93K0.07IrO4 samples, this band evolves into a sharp, well-defined quasiparticle band. Comparisons of the individual EDCs at k = (0, 1.2π) from the doped and undoped samples are shown in Fig. 3e, showing that the broad Ieff = 1/2 excitations in Sr2IrO4 evolve into a well-defined quasiparticle peak for Sr1.93K0.07IrO4. In Fig. 3b, d, we compare spectra from Sr2IrO4 and Sr1.93K0.07IrO4 around (π/2, π/2) in the doped compound intersects the small, elliptical electron pockets as is clear from the momentum distribution curve (MDC) at E_F (Fig. 3d). Corresponding EDCs from Sr2IrO4 and Sr1.93K0.07IrO4 taken at k = (π/2, 0.6π) are shown in Fig. 3e. The lack of a large, uniform pseudogap (we observe a leading edge midpoint of less than 5 meV—see Supplementary Note 3— which is substantially less than the 30 meV shift reported in the Rh-doped samples12,13), and the presence of quasiparticle peaks, which are absent in Sr2Ir1−xRhO4, are both consistent with lower disorder scattering, in the absence of substitutional disorder directly in the IrO2 plane.

**Tight-binding model.** A key distinction between Sr1.93K0.07IrO4 and earlier studies of Sr2Ir1−xRhO4 is the clear presence of elliptical electron pockets, shown both in the Fermi surface map in Fig. 2b and in the band dispersion in Fig. 3d, which were not observed in Sr2Ir1−xRhO4. To better understand the origin of these features, we employ a tight-binding parametrization of the t2g bands following refs. 8,33,34, which has previously shown good agreement with photoemission data8:

\[
\mathcal{H} = \sum_{\langle ij \rangle \alpha \beta \sigma} t^{ij}_{\alpha \beta} \hat{c}_{i \alpha \sigma} \hat{c}_{j \beta \sigma} + \sum_{\alpha \sigma} \Delta \hat{c}_{\alpha \sigma} \hat{c}_{\alpha \sigma}^\dagger + \lambda \sum_{i} \hat{L}_{i} \cdot \vec{S}_{i},
\]

where \(\langle ij \rangle\) are nearest-neighbour pairs of Ir sites, \(\alpha, \beta\) index the \(t_{2g}\) orbitals, \(t_0 = 0.35\) eV, \(\sigma\) indicates the spin, \(\Delta t = 0.15\) eV is the tetragonal crystal field splitting and \(\lambda = 0.57\) eV is the SOC parameter. These are the same values used in ref. 8. The Coulomb repulsion \(U\) is implemented as an additional self-consistent mean-field term, which is proportional to the average electron density of each band. Additional details of the calculation can be found in Supplementary Note 4.

In Fig. 4, we show the tight-binding band structure together with extracted experimental dispersions from both Sr2IrO4 and Sr1.93K0.07IrO4. We find good agreement in both the isoenergy maps (Fig. 2a) and extracted band dispersions (Fig. 4a) for the undoped case for a value of \(U = 2\) eV, consistent with earlier studies of undoped Sr2IrO4.8 Rigidly shifting \(x\) into the top of the \(I_{\text{eff}} = 1/2\) band of this band structure would result in a Fermi surface comprised solely of hole pockets centred at (π, 0) and (0, π), as shown in Fig. 4b. This is reminiscent of the Fermi surface of Sr2Ir1−xRhO4, where it was argued that the Mott gap is largely preserved up to a hole doping of \(x = 0.20\)9,10,12,13, but counter to our observations in Sr1.93K0.07IrO4.

A few important distinctions can be made between 7% hole-doped Sr2−xKxIrO4 and Sr2Ir0.93Rh0.07O4 with a comparable hole doping from ref. 12. First, the top of the \(I_{\text{eff}} = 1/2\) band at (π,0) differs by approximately 0.1 eV (approximately +0.04 eV above \(E_F\) for Rh-doped, approximately −0.15 above \(E_F\) for K-doped). This demonstrates that Sr2Ir0.93Rh0.07O4 is consistent with the rigid band shift scenario in Fig. 4a. Although Sr2Ir0.93Rh0.07O4 only shows appreciable spectral weight near \(E_F\) around (π,0), albeit without sharp spectral features, Sr1.93K0.07IrO4 possesses a two-sheet Fermi surface comprised of sharp, well-defined quasiparticle bands. In particular, the two-pocket fermiology observed in Sr1.93K0.07IrO4 strongly suggests a scenario where the Mott gap has collapsed when \(U\) becomes sufficiently small (Fig. 4d−f), as the elliptical electron pocket originates from the upper Hubbard band itself. Although our data stands in clear contrast to studies of Sr2Ir1−xRhO4, it bears qualitative resemblance to the case of electron doping in Sr2−xLa2IrO4, where both hole and electron pockets have likewise been reported8. Nevertheless, electron vs. hole doping can be clearly distinguished from the relative sizes of the hole and electron pockets, as shown in Fig. 4e, f.

This striking similarity between electron-doped Sr2−xLa2IrO4 and hole-doped Sr2−xKxIrO4 in the global quasiparticle band structure and Fermi surface topology, apart from a shift in the chemical potential, is unexpected given the differences in the internal structure of the doped electrons (Ir 5d6 in a simple \(I_{\text{eff}} = 0\) state) vs. doped holes (Ir 5d4 with a complex spin−orbit-coupled
multiplet structure). This surprising apparent symmetry between electron and hole doping should motivate future many-body calculations (e.g., Hubbard, $t$–$J$ model, or dynamical mean-field theory calculations), which explicitly consider the complex multiplet structure of hole-doped Sr$_2$IrO$_4$.

Despite the apparent symmetry of the global electronic structure upon both electron and hole doping, there remain important distinctions between the two systems at the lowest energy scales. Whereas the electron-doped iridates (surface K or La substitution) in a similar doping range exhibit a large (20 meV), $d$-wave-like pseudogap at $E_F$, we do not experimentally resolve a pseudogap to within 5 meV.

**Discussion**

The differences between Sr$_{2-x}$K$_x$IrO$_4$ and Sr$_{1.93}$K$_{0.07}$IrO$_4$ allow us to elucidate the intrinsic effects of hole doping vs. the additional effects caused by Rh substitution. The lack of electron pockets in the Rh-doped materials is suggestive of a rigid band shift scenario where the Mott gap is largely preserved, in contrast to Sr$_{2-x}$K$_x$IrO$_4$, where we find that the Mott gap collapses and coherent quasiparticle excitations are formed. A possible explanation is that structural and magnetic disorder in the IrO$_2$ planes may cause holes to be strongly localized around Rh dopants, inhibiting free carriers from effectively screening the Mott gap, whereas for the K-doped materials, the carriers are...
more delocalized and are thereby able to more efficiently screen the strong Coulomb interactions. In addition, the existence of coherent quasiparticle peaks and the lack of a large pseudogap in Sr$_{2-x}$K$_x$IrO$_4$ also suggests that the incoherent metallic and the large pseudogap reported in Sr$_{2}$Ir$_{1-x}$Rh$_x$O$_4$ are likely induced by substitutional disorder in the IrO$_2$ plane, rather than an intrinsic property of hole-doped iridates.

Our findings point towards a universal underlying electronic structure upon doping Sr$_2$IrO$_4$, irrespective of the sign of the carriers, and thus a more symmetric doping phase diagram than previously realized. This stands in contrast to the cuprates, which exhibit a fundamental asymmetry between electron and hole doping.90-92 Whereas the evolution of the Fermi surface contours in electron-doped cuprates can be qualitatively modelled by introducing a ($\pi$, $\pi$) spin–density wave via a conventional weak coupling phenomenology,93-96 explaining the disconnected Fermi arcs

Another distinction is that the cuprates are charge-transfer insulators where both the hole- and electron-doped states have stronger O 2p vs. Cu 3d orbitals, respectively, whereas the iridates are better described as Mott insulators where both the hole- and electron-doped states are of primarily Ir 5d orbital character, although they have very different internal magnetic structure.97-99 Future work including detailed doping dependence of the electronic structure and magnetism, and a study of the electronic structure with advanced many-body techniques such as dynamical mean-field theory in electron-doped Sr$_2$IrO$_4$, will be necessary to fully explain the collapse of the Mott gap in hole-doped Sr$_2$IrO$_4$ and the symmetric, universal electronic structure upon both hole and electron doping.

Methods

Film growth. Epitaxial Sr$_2$IrO$_4$(001) thin films were grown on single-crystalline (LaAlO$_3$)$_0.3$(SrAl$_{1/2}$Ta$_{1/2}$O$_3$)$_0.7$ substrates by MBE at a substrate temperature of 850 °C as measured by an optical pyrometer with a measurement wavelength of 20. Okabe, H., Isobe, M., Takayama-Muromachi, E., Takeshita, N. & Akimitsu, J. Carrier doping effect for transport properties of a spin-orbit Mott insulator Sr$_2$IrO$_4$. Nature COMMUNICATIONS | https://doi.org/10.1038/s41467-020-16425-z ARTICLE

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Author contributions

J.N.N. performed the ARPES measurements and synthesized the thin films, with assistance from C.T.P., B.D.F., and J.K.K., and guidance from D.G.S. and K.M.S. J.N.N. performed the tight-binding calculations. J.N.N. and K.M.S. conceived the project and wrote the manuscript with contributions from all authors. K.M.S. supervised the project.

Competing interests

The authors declare no competing interests.

Additional information

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