A Mott insulator continuously connected to iron pnictide superconductors

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Iron-based superconductivity develops near an antiferromagnetic order and out of a bad-metal normal state, which has been interpreted as originating from a proximate Mott transition. Whether an actual Mott insulator can be realized in the phase diagram of the iron pnictides remains an open question. Here we use transport, transmission electron microscopy, X-ray absorption spectroscopy, resonant inelastic X-ray scattering and neutron scattering to demonstrate that NaFe1−xCuxAs near x ≈ 0.5 exhibits real space Fe and Cu ordering, and are antiferromagnetic insulators with the insulating behaviour persisting above the Néel temperature, indicative of a Mott insulator. On decreasing x from 0.5, the antiferromagnetic-ordered moment continuously decreases, yielding to superconductivity \( T_c \approx 0.05 \). Our discovery of a Mott-insulating state in NaFe1−xCuxAs thus makes it the only known Fe-based material, in which superconductivity can be smoothly connected to the Mott-insulating state, highlighting the important role of electron correlations in the high-\( T_c \) superconductivity.

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At the heart of understanding the physics of the iron-based superconductors is the interplay of superconductivity, magnetism and bad-metal behaviour. A key question is whether superconductivity emerges due to strong electronic correlations or nested Fermi surfaces. Superconductivity occurs in the vicinity of antiferromagnetic (AF) order, both in the iron pnictides and iron chalcogenides. In addition, the normal state has a very large low temperature resistivity, which reaches the Ioffe–Mott–Regel limit. This bad-metal behaviour has been attributed to the proximity to a Mott transition, with the Coulomb repulsion of the multi-orbital 3d electrons of the Fe ions being close to the threshold for electronic localization. In the iron chalcogenide family, several compounds show a Mott localization from the combined effects of doping from 3d to 4f, blockage of the kinetic motion of the Fe 3d electrons due to the presence of a covalent bond between the Fe and As atoms, and becomes an AF insulator when x approaches 0.5, highlighting the role of electronic correlations in iron pnictides.

### Results

**Resistivity measurements.** Single crystals of NaFe$_{1-x}$Cu$_x$As were prepared using the self-flux method. Transport measurements were carried out using a commercial physical property measurement system with the standard four-probe method (the Methods section). Figure 1c shows the temperature dependence of the in-plane resistivity for the x = 0.18 sample. In addition to superconductivity at T$_c$ = 11 K, the normal state resistivity ρ is ∼0.4 mΩ cm at room temperature, consistent with previous work. Figure 1f plots the temperature dependence of the resistivity on a log scale for samples with x = 0.18, 0.38, 0.44 and 0.48. Resistivity in the x = 0.18 sample exhibits an enhanced characteristic behaviour consistent with earlier work. For the x = 0.39 samples, resistivity further increases by an order of magnitude compared to the x = 0.18 sample, signifying that electrons become more localized in NaFe$_{1-x}$Cu$_x$As, when x approaches 0.5.

**Neutron scattering results on NaFe$_{0.56}$Cu$_{0.44}$As.** Unpolarized and polarized neutron elastic scattering were carried out on NaFe$_{1-x}$Cu$_x$As single-crystal samples (the Methods section). For these measurements, we use the orthorhombic unit cell notation suitable for the AF-ordered state of NaFeAs (refs 22, 23), and define momentum transfer Q in three-dimensional reciprocal space in Å$^{-1}$ as $Q = 2\pi a^* + 2\pi b^* + 2\pi c^*$, where H, K and L are Miller indices and $a^* = 2\pi/\alpha$, $b^* = 2\pi/\beta$ and $c^* = 2\pi/\gamma$. Single crystals are aligned in the (H, 0, L) and (H, H, L) scattering planes in these measurements. In the (H, 0, L) scattering geometry, the collinear magnetic structure in NaFeAs (Fig. 1c) gives magnetic Bragg peaks below T$_N$ at Q$_{\text{AF}} = (H, 0, L)$, where H = 1, 3, ⋯ and L = 0.5, 1.5, ⋯ positions.

Figure 2c shows typical elastic scans for NaFe$_{0.56}$Cu$_{0.44}$As along the [H, 0, 0.5] direction at T = 3.6 and 300 K. Because of twinning in the orthorhombic state, this is equivalent to elastic scans along the [0, K, 0.5] direction. While the scattering has a clear peak centred around Q = (1, 0, 0.5)(0, 1, 0.5) at room temperature, the scattering is enhanced markedly on cooling to 3.6 K, suggesting the presence of static AF order. The temperature difference plot between 3.6 and 300 K in Fig. 2d indicates that the low-temperature intensity gain is essentially instrumental resolution limited (horizontal bar). Figure 2e shows the temperature difference along the [1, 0, L]/[0, 1, L] direction that apparently is not resolution limited. The temperature dependence of the scattering at (1, 0, 0.5)/(0, 1, 0.5) plotted in Fig. 2f reveals clear evidence of magnetic ordering below T$_N$ ≈200 K, suggesting that the small peak observed at room temperature in Fig. 2c occurs in the paramagnetic phase and is thus of structural (super-lattice) origin induced by Cu substitution, since such a peak is forbidden for NaFeAs.

Fe and Cu ordering in NaFe$_{1-x}$Cu$_x$ with x ≈0.5. To conclusively determine the origin of super-lattice peaks and the crystal structure of NaFe$_{0.56}$Cu$_{0.44}$As, we have carried out high-resolution TEM measurements. The inset in Fig. 2a shows an image of the sample, and the electron diffraction patterns were collected from areas ~100 nm in diameter within a single domain of the sample (see the arrow in the inset of Fig. 2a). A typical diffraction pattern along the [001] zone axis at room temperature is shown in Fig. 2a. While we see clear super-lattice reflections at H = 1, 3, ⋯ positions along the [H, 0, 0] direction,
they are absent at the $K = 1, 3, \cdots$ positions along the $[0, K, 0]$ direction (Fig. 2b). This means that the crystal structure of NaFe$_{0.56}$Cu$_{0.44}$As is orthorhombic and obeys two-fold rotational symmetry. From this information and from intensities of the super-lattice peaks in $(H, 0, L)$ scattering plane, we conclude that Fe and Cu atoms in NaFe$_{0.56}$Cu$_{0.44}$As (which is approximated by NaFe$_{0.56}$Cu$_{0.44}$As) form a real space stripe-like-ordered structure in Fig. 1d, in the space group $Ibam$ (Supplementary Note 1; Supplementary Table 1). This conclusion is further corroborated by single-crystal neutron diffraction measurements (Supplementary Table 2). The Fe–Cu ordering is a structural analogue of the magnetic order in NaFeAs and structural super-lattice peaks occur at the same positions as magnetic peaks in NaFeAs. Fe and Cu ordering in NaFe$_{1-x}$Cu$_x$As affects the intensities of Bragg peaks already present in NaFeAs very little (Supplementary Note 1; Supplementary Fig. 1), and the induced

Figure 1 | Summary of transport and neutron scattering results. (a) The crystal structure of ACu$_2$As$_2$ in the tetragonal state, where $a_{\|}$ is the in-plane lattice parameter. The As–As covalent bonding distance is $\sim$ 2.5 Å. (b) The crystal structure of NaFe$_{1-x}$Cu$_x$As, where similar As–As covalent bonding is not possible. (c) The collinear magnetic structure of NaFeAs, where the AF order and moment direction are along the orthorhombic $a$ axis$^{22,23}$. Only Fe atoms are plotted in the figure for clarity. (d) Real space structure and spin arrangements of NaFe$_{0.5}$Cu$_{0.5}$As in the AF orthorhombic unit cell similar to NaFeAs. In NaFe$_{0.5}$Cu$_{0.5}$As, since Fe and Cu form stripes, Na and As also shift slightly from their high-symmetry positions. (e) In-plane resistivity for $x = 0.016$ sample, where bulk superconductivity occurs below $T_c = 11$ K (ref. 20). (f) Temperature dependence of the in-plane resistivity for $x = 0.18, 0.39, 0.44$ and 0.48 samples. The vertical arrow marks the position of $T_N$ for the $x = 0.44$ sample determined from neutron scattering. (g) Evolution of ordered moment with doping in NaFe$_{1-x}$Cu$_x$As. The two ordered phases are separated by the superconducting dome marked as SC, with no magnetic order for $x = 0.016$ near optimal superconductivity. The right and left insets show the in-plane magnetic structures of NaFeAs and the new AF insulating phase, respectively. For $x \leq 0.05$, the phase diagram from ref. 20 is plotted. Vertical error bars are from least-square fits (1 s.d.).
super lattice are relatively weak. Aside from ordering of Fe and Cu, other aspects of the structure of NaFe\textsubscript{1-x}Cu\textsubscript{x}As remain identical to that of NaFeAs, corroborated by the similar neutron powder diffraction patterns (Supplementary Note 1; Supplementary Fig. 2; Supplementary Table 3).

Magnetic structure of NaFe\textsubscript{1-x}Cu\textsubscript{x}As with x \approx 0.5. Having established the real space Cu and Fe ordering and crystal structure of NaFe\textsubscript{0.56}Cu\textsubscript{0.44}As, it is important to determine the magnetic states of Cu and Fe. Assuming that the covalent As–As bonding is not possible because of the large distance between the
neighbouring As ions (Fig. 1b), As ions in NaFe$_{1-x}$Cu$_x$As can only be in the As$^3-$ state. From XAS and RIXS experiments on NaFe$_{0.56}$Cu$_{0.44}$As (Supplementary Note 2; Supplementary Fig. 3), we conclude that Cu in NaFe$_{1-x}$Cu$_x$As is in the nonmagnetic Cu$^{1+}$ configuration. As a consequence, Fe should be in the Fe$^{3+}$ + 3d$^3$ state, since Na can only be in the Na$^{1+}$ state.

Assuming Fe in NaFe$_{0.56}$Cu$_{0.44}$As is indeed in the Fe$^{3+}$ + 3d$^3$ state, we can determine the magnetic structure of the system by systematically measuring magnetic peaks at different wave vectors (Supplementary Note 3; Supplementary Figs 4 and 5) and using neutron polarization analysis (Supplementary Note 3; Supplementary Fig. 6). By polarizing neutrons along the direction of the momentum transfer $Q$, neutron spin-flip (SF) scattering is sensitive to the magnetic components perpendicular to $Q$, whereas the non-SF (NSF) scattering probes pure nuclear scattering$^{29,32}$. Figure 2g shows SF and NSF scans along the [H, 0, 0.5]/[0, K, 0.5] direction at T = 2 and 240 K. Inspection of the data reveals clear magnetic scattering at 2 K that disappears at 240 K, in addition to the temperature-independent NSF nuclear super-lattice reflection. Figure 2h shows the SF and NSF scans along the [H, H, 0] direction at 2 and 240 K. While the SF scattering shows a clear peak at 2 K that disappears on warming to 240 K, the NSF scattering shows no evidence of the super-lattice peaks. From these results and from systematic determination of magnetic and super-lattice scattering intensity at different wave vectors, we conclude that NaFe$_{0.56}$Cu$_{0.44}$As forms a collinear magnetic structure with moments aligned along the a axis as shown in the right inset in Fig. 1g. The ordered magnetic moment is 1.12 ± 0.09 $\mu_B$/Fe at 4 K determined from neutron powder diffraction (Supplementary Fig. 2e). For this magnetic structure, magnetic peaks are expected and observed at (0, 1, 0.5) and (1, 1, 0) as shown in Fig. 2g(h) (Supplementary Fig. 7). The magnetic peaks at (0, 1, 0.5) overlap with super-lattice peaks at (1, 0, 0.5) due to twinning.

Doping dependence of magnetic order in NaFe$_{1-x}$Cu$_x$As. To determine the Cu-doping dependence of the NaFe$_{1-x}$Cu$_x$As phase diagram, we carried out additional measurements on single crystals of NaFe$_{1-x}$Cu$_x$As with $x$ = 0.18 and 0.39. Figure 3a,b compare the wave vector scans along the [H, 0, 0.5]/[0, K, 0.5] and [1, 0, L]/[0, 1, L] directions for $x$ = 0.18, 0.39 and 0.44. In each case, the scattering intensity is normalized to the (2, 0, 0) nuclear Bragg peak. With increasing Cu doping, the scattering profile becomes narrower and stronger, changing from a broad peak indicative of the short-range magnetic order in $x$ = 0.18 and 0.39 to an essentially instrument resolution limited peak with long-range magnetic order at $x$ = 0.44. Figure 3c shows the doping evolution of the spin–spin correlation length $\xi$ in NaFe$_{1-x}$Cu$_x$As, suggesting that the increasing spin correlations in NaFe$_{1-x}$Cu$_x$As are related to the increasing Cu doping and the concomitant increase in correlation length of Fe and Cu ordering (Supplementary Note 3; Supplementary Fig. 5f). The evolution of the temperature dependent magnetic order parameter with Cu doping is shown in Fig. 3d. For $x$ well < 0.5, the magnetic transition is gradual and spin-glass-like. However, with $x$ approaching 0.5, the transition at $T_N$ becomes more well defined. In the undoped state, NaFeAs has a small ordered moment of 0.17 ± 0.03 $\mu_B$/Fe (ref. 23). On small Cu doping, superconductivity is induced at $x$ = 0.02 and the static AF order is suppressed$^{20}$. With further Cu doping, the system becomes an AF insulator, where the ordered moment reaches ~1.1 $\mu_B$/Fe at $x$ = 0.44 (the ordered moment per Fe site was determined in the structure for NaFe$_{0.5}$Cu$_{0.5}$As (Fig. 1d)). Since the iron moment in NaFe$_{1-x}$Cu$_x$As increases with increasing Cu doping, our determined moment is therefore a lower bound for the ordered moment for Fe in the ideal NaFe$_{0.5}$Cu$_{0.5}$As, which for Fe 3d$^2$ can be in either $S = 3/2$ or $S = 5/2$ spin state.

**Discussion**

The behaviour in NaFe$_{1-x}$Cu$_x$As is entirely different from the bipartite magnetic parent phases seen in the iron oxynitride superconductor LaFeAsO$_1-y$F$_y$, where magnetic parent phases on both sides of the superconducting dome are metallic antiferromagnets$^{33}$. In Cu-doped Fe$_{1-x}$Cu$_x$Se, a metal–insulator transition has been observed ~4% Cu doping, and a localized moment with spin glass behaviour is found near $x$ = 0.12 (refs 34,35). Although the density functional theory (DFT) calculations suggest that Cu occurs in the 3d$^{10}$ configuration and the metal–insulator transition is by a disorder induced Anderson localization in Fe$_{1-x}$Cu$_x$Se (ref. 36), the 20–30% solubility limit of the system$^{34}$ means it is unclear whether Fe$_{1-x}$Cu$_x$Se is also an AF insulator at $x$ ≈ 0.5.

It is useful to compare our experimental findings with the results of the band structure calculations based on DFT (the Methods section; Supplementary Note 4; Supplementary Figs 8–10). Both the DFT and DFT + U calculations clearly predict the paramagnetic phase of NaFe$_{0.5}$Cu$_{0.5}$As to be a metal (Supplementary Fig. 9). By contrast, our measurements have shown that the isolating behaviour of the resistivity persists above the Néel temperature (Fig. 1), implying that NaFe$_{0.5}$Cu$_{0.5}$As is a Mott insulator. This is also consistent with STM measurements on lower Cu-doping NaFe$_{1-x}$Cu$_x$As, where the overall line shape of the electronic spectrum at $x$ = 0.3 is similar to those of lightly electron-doped copper oxides close to the parent Mott insulator$^{37}$. To understand the origin of the Mott-insulating behaviour, we address how Cu doping affects the strength of electron correlations (the Methods section; Supplementary Note 5; Supplementary Figs 11 and 12). Our starting point is that the local (ionization) potential difference between the Fe and Cu ions, as illustrated in Fig. 4a and described by the energy shift $\Delta$ in Fig. 4b, will suppress the hopping integral between Fe and Cu sites. This causes a reduction in the kinetic energy or, equivalently, the electronic bandwidth. The ratio of the on-site Coulomb repulsion $U$ (including the Hund’s coupling $J_H$) relative to the bandwidth will effectively increase, even if the raw values of $U$ and $J_H$ remain the same as in pure NaFeAs. This would enhance the tendency of electron localization even without considering the disorder effects with increasing $x$ (refs 37,38).

The case of $x = 0.5$ allows a detailed theoretical analysis. Here, the Cu and Fe ions in NaFe$_{1-x}$Cu$_x$As have real space ordering, as discussed above. We study the metal–insulator transition in multi-orbital Hubbard models for NaFe$_{0.5}$Cu$_{0.5}$As via the U(1) slave-spin mean-field theory$^{30}$. We use the tight-binding parameters for NaFeAs, and consider the limit of a large local potential difference between Cu and Fe, which transfers charge from Fe to Cu to Cu$^{1+}$ (n = 10). The fully occupied Cu 3d shell makes the Cu ions essentially as vacancies. Reduction of the Fe 3d electron bandwidth is caused by this kinetic blocking effect (Supplementary Fig. 11). The resulting ground-state phase diagram is shown in Fig. 4c. For realistic parameters, illustrated by the shaded region, a Mott localization takes place. Our understanding is in line with the general theoretical identification of a Mott-insulating phase in an overall phase diagram$^{30}$, which takes into account a kinetic energy reduction induced increase of the effective interactions and a decrease of the 3d electron-filling from 6 per Fe$^{2+}$ to 5 per Fe$^{3+}$ (refs 7,9–11,30).

Our work uncovers a Mott insulator, NaFe$_{0.5}$Cu$_{0.5}$As, and provides its understanding in an overall phase diagram of both bandwidth and electron-filling controls$^{30}$. Our results suggest that
the electron correlations of the iron pnictides, while weaker than those of the iron chalcogenides, are sufficiently strong to place these materials in proximity to the Mott localization. This finding makes it natural that the electron correlations and the associated bad-metal behaviour and magnetism induce a similarly high superconducting transition temperature in the iron pnictides as in the iron chalcogenide family. Such a commonality, in spite of the very different chemical composition and electronic structure of these two broad classes of materials, introduces considerable simplicity in the quest for a unified framework of the iron-based superconductivity. More generally, the proximity to the Mott transition links the superconductivity of the iron pnictides to that arising in the copper oxides, organic charge-transfer salts and alkali-doped fullerides, and suggests that the same framework may apply to all these strongly correlated electronic systems.

Note added after submission: very recently, angle-resolved photoemission spectroscopy measurements on NaFe$_{0.56}$Cu$_{0.44}$As single crystals has confirmed its Mott-insulating nature.

**Methods**

**Sample preparation and experimental details.** NaFe$_{1-x}$Cu$_x$As single crystals were grown by the self-flux method using the same growth procedure as for NaFe$_{1-x}$Co$_x$As described in earlier work. The Cu-doping levels used in this paper were determined by inductively coupled plasma atomic-emission spectroscopy. Samples with nominal Cu concentrations of $x = 0.2$, 0.5, 0.7, and 0.9 were prepared, resulting in actual Cu concentrations of $x = 1.6$, 1.8, 1.9, 3.8, 4.2, 4.4, and 4.8. Each nominal doping except $x = 2$, five to six samples were measured and the s.d. in these measurements are taken as the uncertainty of the actual concentrations. For simplicity, the actual concentrations are noted as $x = 1.6$, 1.8, 1.9, 3.8, 4.2, 4.4, and 4.8% in the rest of the paper. This suggests that the solubility limit of Cu in NaFe$_{1-x}$Cu$_x$As single crystals by our growth method is $\approx 50\%$.

For resistivity measurements, samples were mounted onto a resistivity puck inside an Ar filled glove box by the four-probe method and covered in Apiezon N grease. The prepared puck is then transferred in an Ar-sealed bottle and is only briefly exposed in air, while being loaded into a physical property measurement system for measurements. After measurements, no visual deterioration of the samples were seen under a microscope.

For single-crystal elastic neutron scattering measurements, samples were covered with a hydrogen-free glue and then stored in a vacuum bottle at all times except during sample loading before the neutron scattering experiment. While our largest crystals grown are up to 2 g, we typically used thin plate-like samples $\approx 5 \times 5 \text{ mm}^2$ in size with mass $\approx 0.2$ g for elastic neutron scattering measurements. Measurement of the sample with $x = 0.18$ was carried out on the N5 triple-axis spectrometer at the Canadian Neutron Beam Center, Chalk River Laboratories. Pyrolic graphite (PG) monochromator and analyser ($\hbar = 1.456 \text{ meV}$) were used with none-36’-sample-33’-144’ collimation set-up. A PG filter was placed after the sample to eliminate contamination from higher-order neutron wavelengths. The experiment on $x = 0.39$ and 0.44 samples were done on the HB-3 triple-axis spectrometer and the HB-1A fixed incident-energy triple-axis spectrometer, respectively, at the High Flux Isotope Reactor, Oak Ridge National Laboratory. On HB-3, a PG monochromator ($\hbar = 14.7 \text{ meV}$), analyser and two PG filters (one before and the other after the sample) were used with collimation set-up 48°–60°-sample-80°–120°. HB-1A uses two PG monochromators ($\hbar = 14.6 \text{ meV}$) and two PG filters (mounted before and after second monochromator), resulting in negligible higher-order wavelengths neutrons in the incident beam. A PG analyser is placed after the sample. The collimation used was 48°–48°-sample-40°–68°. In all cases above, the samples were aligned in [H, 0, L] scattering plane.

The polarized single-crystal neutron scattering measurements were carried out on the C5 polarized beam triple-axis spectrometer at Canadian Neutron Beam Center, Chalk River Laboratories. The neutron beams were polarized with Heusler (1, 1, 1) crystals with a vertically focusing monochromator and a flat analyser ($\hbar = 13.70 \text{ meV}$). A PG filter was placed after the sample and none-48°–51°–144° collimation was used. Neutron polarization was maintained by using permanent magnet guide fields. Mezei flippers were placed before the sample to allow the measurement of neutron SF and NSF scattering cross-sections. A 5-coil Helmholtz assembly was used to control the neutron spin orientation at the sample position by producing a magnetic field of the order of 10 G. The orientation of the magnetic field at the sample position was automatically adjusted to allow the measurements to be performed for the neutron spin to be parallel or perpendicular to the momentum transfer. The flipping ratio, defined as the ratio of nuclear Bragg peak intensities in NSF and SF channels, was measured to be $\approx 10:1$ for various field configurations. The sample was studied in both [H, 0, L] and [H, H, L] scattering planes.

The XAS and RIXS measurements on the $x = 0.44$ samples were carried out at the Advanced Resonant Scattering beamline of the Swiss Light Source, Paul Scherrer Institut, Switzerland. Samples were cleaved in situ and measured in a
Figure 4 | Schematic 3d electronic states and parameter regimes of a Mott insulator in the theoretical phase diagram for NaFe$_{0.5}$Cu$_{0.5}$As.

Schematic of the electronic states of a Cu ion alongside those of an Fe ion, shown in terms of the atomic levels (a) and the electronic density of states (b). The relative potential difference associated with the two ions is specified in terms of an energy shift, $\Delta$, as illustrated in b. c) The ground-state phase diagram of a multi-orbital Hubbard model for NaFe$_{0.5}$Cu$_{0.5}$As. $U_{\text{OSM}}$ and $U_{\text{MT}}$ refer to the critical $U$ values for an orbital-selective Mott (OSM) transition and a Mott transition (MT), respectively, into an orbital-selective Mott phase (OSMP) and a Mott insulator. The shaded region shows the physical parameter regime as determined by comparing the theoretically calculated bandwidth renormalization factors of the three $t_{2g}$ orbitals with those determined by the angle-resolved photoemission spectroscopy (ARPES) results (Supplementary Note 5).

vacuum better than $1 \times 10^{-10}$ mbar. X-ray absorption was measured in total electron yield mode by recording the drain current from the samples and in total fluorescence yield with a photodiode. Linearly polarized X-rays with $E = 931.8$ eV resonant on the Cu $L_3$ edge were used for the RIXS measurements. The total momentum transfer was kept constant, but the component of momentum transfer in the $ab$ plane has been varied.

For neutron powder diffraction measurements, the samples were ground from $2 g (x = 0.016, 0.18, 0.39$ and $0.64$) of single crystals and sealed in vacuum sample cans inside a He-filled glove box. Neutron powder diffraction measurements were carried out at room temperature (300 K) on the BTI high-resolution powder diffractometer at NIST Center for Neutron Research. The Ge(3, 1, 1) monochromator was used to yield the highest neutron intensity and best resolution at low scattering angles. For the $x = 0.44$ sample, measurement at $4 K$ using a Cu(3, 1, 1) monochromator was also carried out.

For the single-crystal neutron diffraction measurement, a sample with $x = 0.44$ (25 mg) was used. The experiment was carried out at the four-circle diffractometer HB-3A at the High Flux Isotope Reactor, Oak Ridge National Laboratory. The data was measured at 250 K with neutron wavelength of 1.003 Å from a bent Si(3, 3, 1) monochromator using an Anger camera detector. Bragg peaks associated with the NaFeAs structure were measured with 1 s per point by carrying out rocking scans. Super-lattice peaks were measured with 10 min per point at each position.

DFT-based electronic structure calculations. To take into account the correlation effects beyond the Hatree–Fock level, we further study the metal–insulator transition in multi-orbital Hubbard models for both NaFeAs and NaFe$_{0.5}$Cu$_{0.5}$As via the $U(1)$ slave-spin mean-field theory. The model Hamiltonian contains a tight-binding part and a local interaction part. Detailed description of the model is given in ref. 49. The tight-binding parameters for NaFeAs are taken from ref. 50, and the electron density is fixed to $n = 6$ per Fe. As for NaFe$_{0.5}$Cu$_{0.5}$As, the very large local potential difference between Cu and Fe, as estimated from our and previous DFT calculations, leads to a charge transferring from Fe to Cu. As a result, Fe is effectively hole doped when the Cu-doping concentration is close to 0.5. This picture is supported by our experimental results which suggest that the Cu is in a 3d$^{10}$ configuration with $n = 10$, and Fe configuration is 3d$^5$ with $n = 5$. As a zeroth-order approximation to the fully occupied Cu 3d shell, we treat Cu ions as vacancies. They organize themselves in a columnar-order pattern in NaFe$_{0.5}$Cu$_{0.5}$As, as shown in Fig. 1d.

Data availability. The data that support the findings of this study are available from the corresponding authors on request.

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**Author contributions**

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**Additional information**

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