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# Superconductivity, pseudo-gap, and stripe correlations in high- $T_c$ cuprates

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## Abstract

Under-doped La-214 cuprates show a charge- and spin-modulation known as “stripes” [1]. These stripe modulations are (quasi)-static close to 1/8 hole doping where superconductivity is suppressed. The pseudo-gap phase of other cuprate compounds recently also revealed charge modulation, but interpreted rather as a charge density wave (CDW) [2, 3, 4], that possibly competes with superconductivity. In this context, to better understand the interplay between the stripe phase and the superconductivity, we use angle-resolved photoemission spectroscopy to study the electronic band structure and gap in La-214 cuprates near 1/8 doping ( $\text{La}_{2-x-y}\text{Nd}_y\text{Sr}_x\text{CuO}_4$  ( $x = 0.12$ ;  $y = 0.0$  &  $0.4$ )) and compare with the previous results in the same system [5] and  $\text{La}_{1.86}\text{Ba}_{0.14}\text{CuO}_4$  [6]. Our data shows a loss of spectral intensity towards the end of the Fermi arcs, that is possibly due to a strong renormalisation, as already pointed out elsewhere

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[5], with a noisy but still measurable gap. On the nodal direction no gap is observed within our statistics, but a sizeable decrease in intensity with temperature. Moreover, we do not see any shadow band, but our Fermi surface can be well modelled with a single electron band calculation in the tight binding approximation, even very close to the 1/8 doping  $\text{La}_{2-x-y}\text{Nd}_y\text{Sr}_x\text{CuO}_4$  with and without Nd substitution.

*Keywords:* cuprates, superconductivity, pseudo-gap, ARPES, stripes, Fermi surface

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## 1. Introduction

The nature of the normal-state gap (pseudo-gap) and its relationship with superconductivity are believed to hold the key for understanding the mechanism of high- $T_c$  superconductivity. In cuprates, the pseudo-gap opens well above  
5 the superconducting critical temperature at moderate doping. Many previous experiments suggest that the pseudo-gap is distinct from superconducting gap and that it opens towards the anti-nodal direction, similar to a  $d$ -wave symmetry. A large body of experimental evidence now suggests that, at least in a small region of the under-doped phase diagram, there is a broken-symmetry state that  
10 is distinct from homogeneous superconductivity. In the “214 family”, the low temperature phase is accompanied by the ordering of charge and spin in a stripe form, where a fraction of carriers forms a charge modulation coexistent with spin modulation in a configuration which is referred to as stripes [7, 8]. Charge-modulations have been proposed as a possible origin of the broken-symmetry  
15 state, either in the stripes [1] or the CDW [9] form. In the region of the phase diagram where these charge-modulations are static, scattering experiments have suggested that they compete with superconductivity [2, 3, 4], although a possible different role of the fluctuating stripes is still debated [1]. We can pin the fluctuating stripes in  $\text{La}_{2-x}\text{Sr}_x\text{CuO}_{4+\delta}$  (LSCO) at  $x = 1/8$  doping, by replacing  
20 Sr with Ba in  $\text{La}_{2-x}\text{Ba}_x\text{CuO}_{4+\delta}$  (LBCO), or with partial substitution of Nd on the La site in  $\text{La}_{2-x-y}\text{Nd}_y\text{Sr}_x\text{CuO}_{4+\delta}$  (LNSCO). Then the charge ordering

in LBCO or LNSCO is static and suppresses superconductivity in a narrow doping region around  $x = 1/8$  [10]. When lowering the temperature, the pinning first appears for the charge component, accompanied by a structural transition  
 25 from the low temperature orthorhombic (LTO) phase to the low temperature tetragonal (LTT) phase below  $T_{LTT}$ . Lowering the temperature even further, the magnetic component is pinned as well below  $T_{stripe}$ . In LSCO, as the charge/spin modulation static component is null [7] or much weaker [11], the impact of the density modulation is mitigated, causing only a slight depression  
 30 in  $T_c$  in the vicinity of  $x = 1/8$  [12] doping.

The link between the anti-nodal pseudo-gap and charge modulations (CDW/stripe phase) is explored by C. Matt and co-workers with an angle-resolved photoemission spectroscopy (ARPES) study of the charge stripe ordered system  $\text{La}_{1.6-x}\text{Nd}_{0.4}\text{Sr}_x\text{CuO}_4$  at  $1/8$  doping [5]. More recently, the nature of the  
 35 pseudo-gap close to the node has been investigated in the 214 LSCO system, but without charge modulation pinning and for low doping [13]. The authors show a link between a spin density wave and the nodal gap. In this work, we report ARPES results for the nearly  $1/8$  doped  $\text{La}_{1.88}\text{Sr}_{0.12}\text{CuO}_4$  and  $\text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{CuO}_4$  in order to study the nature of the pseudo-gap and its re-  
 40 lationship with superconductivity, as well as its possible link to the spin/charge modulations.

## 2. Methods and experimental details

High-quality single crystals of nearly  $1/8$  doped  $\text{La}_{1.88}\text{Sr}_{0.12}\text{CuO}_4$  and  $\text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{CuO}_4$  were grown from the melt in an image furnace by the travelling  
 45 solvent floating zone (TSFZ) method under a pressure of 3 bar oxygen at the ICMMO, Orsay. The  $T_c$  were measured and determined from the susceptibility measurement by the MPMS (QuantumDesign) SQUID magnetometer available at the MPBT facility of the UPMC University (Paris, France), shown in Figure 1 (a) and 1 (b). The onset temperatures of the superconducting transition  $T_c$  are  
 50 31 K for LSCO and 4.6 K for LNSCO, respectively. The structural and magnetic

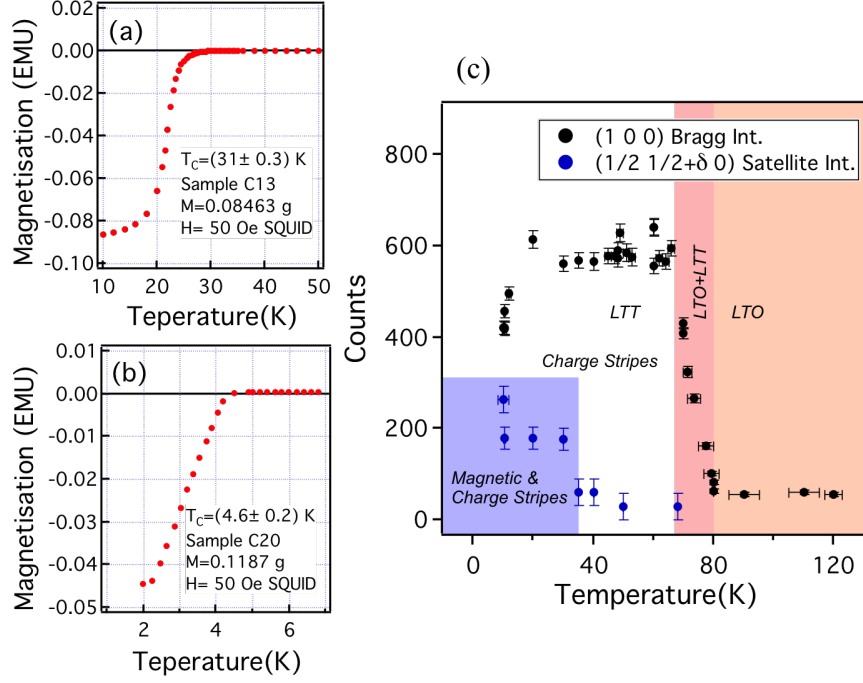


Figure 1: (Color online). The magnetisation measurements of (a)  $\text{La}_{1.88}\text{Sr}_{0.12}\text{CuO}_4$  (sample C13) and (b)  $\text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{CuO}_4$  (sample C20). Temperature dependence of the magnetisation under a field of 50 Oe for the zero-field cooled condition. (c) Phase diagram of  $\text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{CuO}_4$  determined by neutron scattering data: the temperature dependence of the super-lattice peak intensities. Blue filled circles: magnetic superlattice peak at the  $(1/2, 1/2 + \delta, 0)$ ,  $\delta \sim x \sim 0.111$ ; Black filled circles:  $(1, 0, 0)$  structural peak allowed only in the LTT phase.

stripes characterisation was made using the 1T 3-axes spectrometer, run by KIT  
 (Karlsruhe, Germany) and the LLB laboratory (Ce-Saclay, France) available at  
 the Orphee neutron source (CE-Saclay, France), in particular to measure  $T_{LTT}$   
 and  $T_{stripe}$ . In Figure 1 (c), we also show the neutron scattering data on the  
 55 LNSCO sample. We observe the intensity of the Bragg reflection  $(1, 0, 0)$ , which  
 is forbidden in the LTO phase yet allowed in the LTT phase, increases at  $\sim 80$  K  
 and saturates at  $\sim 70$  K. At this temperature, the charge modulations (stripes)  
 are known to appear [7]. Below 35 K, we observe additional intensity on the  
 satellite of the magnetic Bragg reflection at  $(1/2, 1/2+\delta, 0)$  due to scattering  
 60 from the magnetic stripes. Therefore, we can identify four different phases in  
 this LNSCO composition with three transition temperatures: a superconducting  
 state below  $T_c \sim 4.6$  K, magnetic stripes state below  $T_{stripe} \sim 35$  K, LTT phase  
 below  $T_{LTT} \sim 70$ –80 K and finally an LTO phase above  $T_{LTT}$ .

The ARPES measurements were performed on the CASSIOPEE-B-ARPES  
 65 beamline of the Synchrotron SOLEIL (Ormes de Merisier, France). This beam-  
 line has the necessary energy and momentum resolution, photon energy, and  
 temperature ranges to allow a fast and systematic exploration of the experimen-  
 tal phase space. The crystals were cut from a larger bar, at a given orientation  
 determined by Laue diffraction in order to fit the cryostat holder. A notch was  
 70 added to guide the cleave parallel to the  $ab$ -plane as much as possible. The  
 crystals were mounted on the rotating head of the cryostat and cleaved in-situ  
 at  $10^{-11}$  mbar and 9 K. In this work, we performed our ARPES measurements  
 of the LNSCO sample at three different temperatures ( $T = 9$  K, 55 K and  
 90 K), to investigate the magnetic stripe phase, charge-only stripe phase, and  
 75 the normal phase.

### 3. Results and discussion

Figure 2 (a) shows a well-defined Fermi surface of LSCO for the compound  
 $x = 0.12$  obtained at  $T = 5$  K in the superconducting states reconstructed from  
 experimental ARPES data measured at 5 K with a photon energy of  $\hbar\omega = 55$  eV,

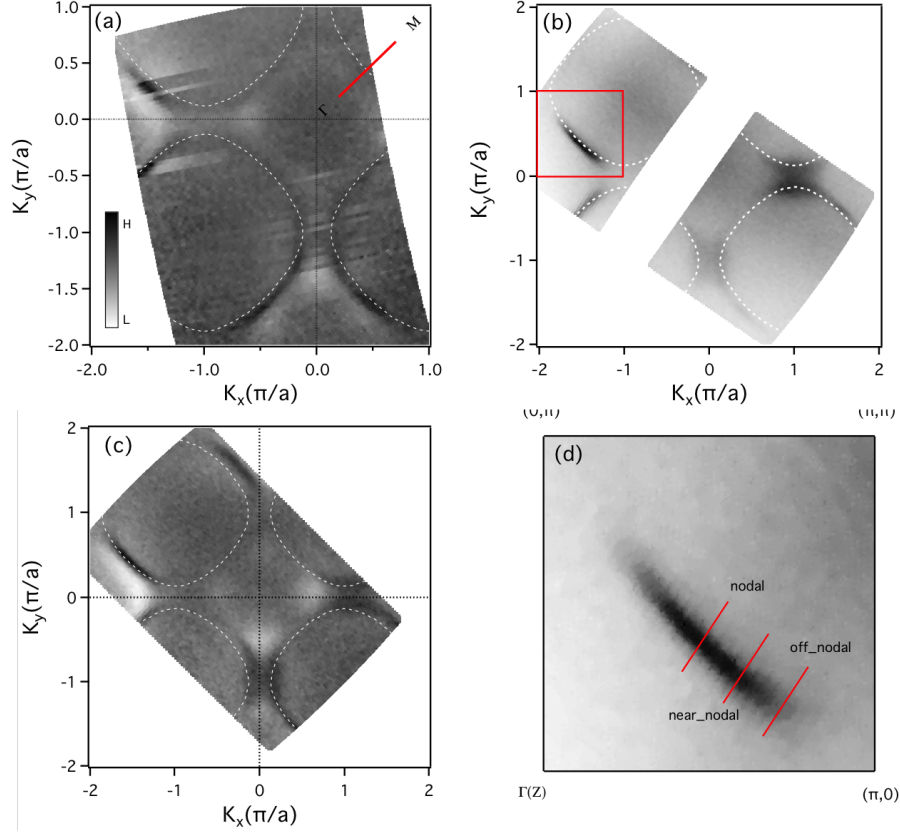


Figure 2: (Color online). Angle-resolved photoemission spectra and the Fermi surface of LSCO and LNSCO. (a) The Fermi surface of  $\text{La}_{1.88}\text{Sr}_{0.12}\text{CuO}_4$  (LSCO) with a large momentum coverage measured at a photon energy of  $\hbar\omega = 55$  eV at  $T = 5$  K (below  $T_c$ ). The dashed curves represent the tight binding Fermi surface results from a global fit to the data as guide to the eye. (b) The same as (a) but at  $T = 55$  K (above  $T_c$ ) (c) The Fermi surface of  $\text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{CuO}_4$  at  $T = 9$  K. (d) Zoom of the section marked in red in pane (b) showing the dispersion cuts along the Fermi surface.

80 which represents the integrated photoelectron intensity of spectra over a small  
 energy window  $E = E_F \pm 10$  meV, normalised using the intensity well above  
 $E_F$ . The normal states Fermi surface are shown in Figure 2 (b) for LSCO and 2  
 (c) for LNSCO. The Brillouin zone guidelines shown in Figure 2 (a) are drawn by  
 ignoring the finite  $k_z$  dispersion in the system, as this is indiscernible within the  
 85 experimental accuracy for the photon energies used. We see a hole-like Fermi  
 surface with a large pocket centred at M ( $\pi, \pi$ ), which is consistent with previous  
 observations in under-doped cuprates. Similar to the Ref. [14], we do not see the  
 shadow bands previously reported in 1/8 doping, which potentially represents  
 additional ingredients in the band structure that goes beyond the single-band  
 90 picture. Indeed, it has been suggested that the shadow band intensity could be  
 even enhanced at  $x = 1/8$  compared with both its lower and higher doping sides  
 [15]. Our data roughly corresponds to what expected from single electron bands  
 calculations in the tight binding approximation (white, dashed line in Figure 2  
 (a)).

95 In Figure 3, we compare the spectral line shapes of the nodal and off-nodal  
 cuts (depicted in Figure 2 (d)) on LSCO samples in the superconducting states  
 and in the normal states. In panel (a), the energy distribution curves (EDCs)  
 integrated over a small interval of  $0.02$  Å around  $k_F$  were obtained along the  
 nodal and off-nodal directions, both below and above  $T_c = 31$  K. We can see  
 100 a discernible quasi-particle peak in the superconducting state as well as in the  
 normal state in the nodal region. In the off-nodal region, in contrast, the spectral  
 weight near  $E_F$  is suppressed both below and above  $T_c$ , as already reported in  
 the region where the pseudo-gap is open [5, 14]. There is no measurable spectral  
 weight difference between data below and above  $T_c$ . In order to estimate the  
 105 size of the energy gap at each  $k_F$ , we symmetrised the ARPES spectrum with  
 respect to  $E_F$  to eliminate the effect from the Fermi-Dirac function [16], and the  
 $E_F$ -symmetrised EDCs are shown in panel (b) and (c). We can observe that, for  
 the LSCO ( $x=1/8$ ) sample, the superconducting gap is opening when we move  
 from the nodal to the off-nodal region at  $T = 5$  K, and persists at  $T = 55$  K,  
 110 well above  $T_c$ , where an almost comparable gap at the off-nodal region is clearly



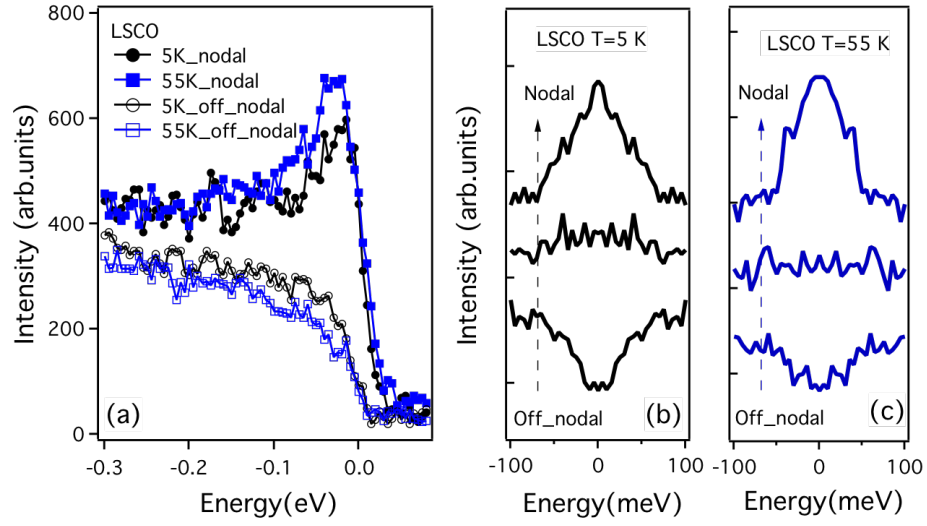


Figure 3: Superconducting gap and pseudo-gap measured by ARPES. (a) Comparison of energy distribution curves (EDCs) at  $k_F$  along the nodal/off-nodal directions below and above  $T_c$  for  $\text{La}_{1.88}\text{Sr}_{0.12}\text{CuO}_4$ . (b) and (c) The  $E_F$ -symmetrised EDCs from the nodal to off-nodal region obtained at  $T = 5 \text{ K}$  and  $T = 55 \text{ K}$ , respectively.

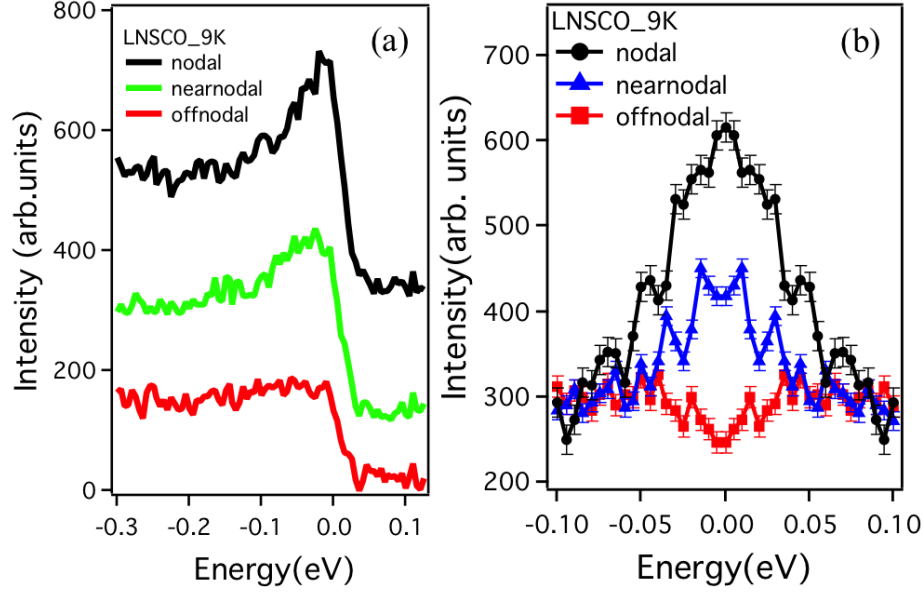


Figure 4: (a) Temperature and momentum dependence of EDCs at 9 K. (b) EDCs of panel (a) symmetrised.

visible, as expected for a pseudo-gap. The spectral evolution with temperature, shown in Figure 3 (c), indicates that the off-nodal pseudo-gap persists deep into the LTO phase. Our observation is consistent with the report of Ref. [17], which also shows that a off-nodal pseudo-gap exists at the 1/8 doping.

115 In order to see the pseudo-gap in the 1/8 doped LNSCO, we show in Figure 4 (a) the EDCs for several cuts in the reciprocal space at  $T = 9$  K, from nodal region to off-nodal region. The EDCs show a fairly weak quasi-particle peak with a high background level along the off-nodal direction. When moving towards the nodal direction, the quasi-particle peak intensity evolves and gets sharp. This  
120 evolution of the quasi-particle peak as function of k-momentum is consistent with general observations: the spectral weight has a maximum near the node and drops off rapidly when approaching the antinode where it is suppressed and finally vanishes, resulting in a broad line-shape with a weak shoulder near  $E_F$ . Despite the evolution of the low-energy spectral weight along the Fermi

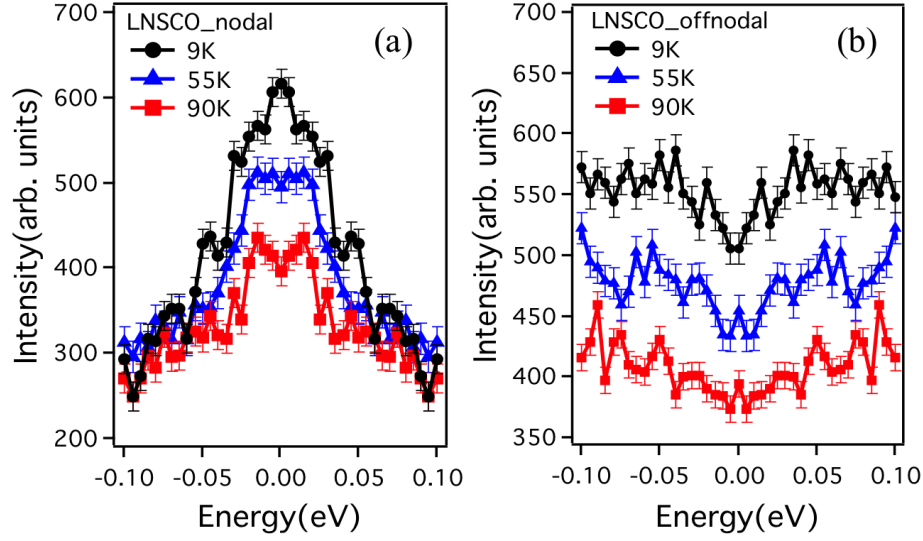


Figure 5: (Color online). Temperature evolution of the nodal pseudo-gap (a) and off-nodal pseudo-gap (b) on 1/8 doped LNSCO shown as symmetrised EDCs.

surface, the quasi-particle peak maintains a distinct structure in momentum space, which gives the possibility to determine the peak position. For example, as shown in Figure 4 (a), we easily see that the peak position tends to move towards higher binding energy indicating an opening of the pseudo-gap with a maximum at the off-node. The raw symmetrised EDCs of LNSCO are shown in Figure 4(b). We can see the opening of the pseudo-gap as the momentum cut goes from the nodal direction towards the off-nodal region at the end of the Fermi arc.

The temperature evolution of the two momentum cuts along the nodal and off-nodal direction are shown in Figure 5, in symmetrised EDCs. In Figure 5 panel (a), despite the very noisy data, a small gap could be seen above 55 K, which would confirm the data shown by Matt and coworkers [5]. This suggests that the pseudo-gap can exist in the nodal region, but would require further measurements in order to have sufficient statistics to confirm the result.

## 4. Conclusions

Our data shows a loss of spectral intensity towards the end of the Fermi arcs, that is possibly due to a strong renormalisation, as already pointed out elsewhere [5], with a noisy but still measurable gap. On the nodal direction no gap is observed within our statistics, but a sizeable decrease in intensity with temperature. Moreover, we do not see any shadow band, but our Fermi surface can be well modelled with a single electron band calculation in the tight binding approximation, even very close to the 1/8 doping, both for LSCO and Nd substituted LNSCO.

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