A Real Space Description of Field Induced Melting in the Charge Ordered Manganites: II. the Disordered Case

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The effect of A site disorder on the magnetic field induced melting of charge order (CO) in half doped manganites has been studied using a Monte-Carlo technique. Strong A-site disorder destroys CO even without an applied field. At moderate disorder, the zero field CO state survives but has several intriguing features in its field response. Our spatially resolved results track the broadening of the first order field melting transition due to disorder, explain the unusual dependence of the melting scales on bandwidth and disorder, and allow an unified understanding of CO melting across all manganites. We also present some results on disorder assisted trapping of metastable phases in the low temperature state as seen in recent experiments.

I. INTRODUCTION

The half-doped state in the manganites has been thoroughly explored in the recent past. In particular, the magnetic field induced melting of the charge order (CO) has been probed experimentally to map out the hysteretic response, and the bandwidth dependence of the magnetic field induced melting of the charge order. We will simply call this the CE-CO-I phase. The applied field at best would convert the CE-CO-I to a FM-CO-I, but not ‘melt’ the charge order. In low disorder systems e.g. Ln$_{0.5}$Ca$_{0.5}$MnO$_3$, this broad trend of increasing melting fields with decreasing $r_A$ has been seen. In our calculations, we have shown that at intermediate magnetic fields, the ground state ceases to be a homogeneous FM-M with density $n = 0.5$ and instead phase separates (PS). The PS is between FM-M and AFM-M at larger $r_A$, and between FM-M and FM-CO at smaller $r_A$. Further, these coexisting phases are all off $n = 0.5$. Thus, the field melted state is at best a percolative metal.

In real life, while low cation mismatch is possible, as in Ln$_{0.5}$Ca$_{0.5}$MnO$_3$, eliminating disorder altogether is difficult. To this end, there is only one attempt to create a disorder free half doped system, but it unfortunately does not probe the nature of the field melted state. In all other conventional experiments, the disorder, although small is enough to mask the effect above.

This brings us to a point where we need to carefully analyse the effects of weak and strong disorder. First, the origin of A-site disorder. In the process of varying the $r_A$, one inevitably introduces disorder due to cation size mismatch. Disorder makes its appearance in two forms, (i) the randomness introduced in the hopping due to random deviations of the Mn-O-Mn bond angles and, (ii) if the valence state of the dopant is different from the parent material, the dopant locations act as scattering centers. The extent of structural disorder is quantified by the variance, $\sigma_A$, of the distribution of the cation radii in $A_{1-x}A^+_{x}\text{BO}_3$ and has been measured for the Ca, Sr, and Ba families. From these measurements it is known that while in the Ca family (Ln$_{0.5}$Ca$_{0.5}$MnO$_3$, where Ln=La, Pr, Nd, Sm, Eu, etc.) $\sigma_A \sim 10^{-3} \AA^2$, for the Sr family (Ln$_{0.5}$Sr$_{0.5}$MnO$_3$) greater size mismatch leads to $\sigma_A \sim 10^{-2} \AA^2$. For the Ba family disorder is large enough to kill the CE-CO-I state completely even without a magnetic field.
In our earlier work\textsuperscript{[21]22} we classified the Ln\textsubscript{0.5}Ca\textsubscript{0.5}MnO\textsubscript{3} family as ‘clean’ with a disorder variance $\sigma_A \sim 10^{-3} \ A^2$, while the Ln\textsubscript{0.5}Sr\textsubscript{0.5}MnO\textsubscript{3} family was classified as disordered with the disorder variance ($\sigma_A \sim 10^{-2} \ A^2$). We describe our modelling of disorder in Section III. In our earlier work we compared our results for ideally clean, $\Delta = 0$, results with the Ca family and that of moderate disorder with the Sr family. While the $\Delta = 0$ results do broadly match with the trends seen in the Ca family (there is a monotonic growth in the critical melting fields $h_{CO}$ with reducing $r_A$) here we demonstrate that $\Delta = 0$ is not crucial and the same trend can be obtained for a window of low $\Delta$.

We also track the disorder induced smearing of the first order transition. Finally, we show that, starting in from $\Delta = 0$ and going up to strong disorder, the essential physics can be rationalized by studying the zero field ‘bandwidth-disorder’ phase diagram.

One is also interested in the spatial nature of the field melted state. This line of work has been picked up only recently. Experiments on weak and moderately disordered system both at half doping and away, e.g. LPCMO\textsuperscript{[12]13}14 show that disorder inhibits the approach to equilibrium, leading to non-equilibrium coexistent states with the phase fractions of the coexistent states being strongly dependent on the path followed to bring the system to its final state.\textsuperscript{[10]111314} In the present work we show results on disorder induced trapping of metastable phase fractions. The detailed nature of the nonequilibrium coexistence and its $h-T$ protocol dependence will be reported elsewhere.

The paper is organised as follows. In section II we summarize the key experimental results and in the following section III define the model and describe the method for solving it. Section IV A. discusses the zero field reference state and the effects of disorder on that. Section IV B and C discusses the effects of disorder on field melting, and in Section IV D, we present our results on disorder assisted trapping of FM-M phase in the low temperature CE-CO-I state. Section V concludes the paper.

II. EXPERIMENTAL RESULTS

Typically, disorder in manganites ABO\textsubscript{3} arise because of A or B site substitutions. In this work we consider the effects of A-site disordering on the melting of the CO-state. We have studied the effects of B-site disorder on the CO state at half doping is studied in\textsuperscript{[14]}

Fig.1.(a)-(b) show the key differences between the clean and the disordered results. These plots, reconstructed from experimental data,\textsuperscript{[27]} present the evolution of the critical switching fields and CO melting temperatures with decreasing $r_A$ (increasing BW) for (a) clean ($\Delta = 0$) and (b) disordered cases. The ± on the critical melting fields $h_{CO}$ stand for the critical melting field as obtained in low temperature magnetic field sweeps in the direction of increasing (+) and decreasing (-) field.

Switching fields are defined as the magnetic field value where the CO volume fraction switches. This is typically concomitant with a sharp change in the resistivity ($\rho$). The labels on top show the A site dopant and (a) is for the Ln\textsubscript{0.5}Ca\textsubscript{0.5}MnO\textsubscript{3} family and (b) is for the Ln\textsubscript{0.5}Sr\textsubscript{0.5}MnO\textsubscript{3} family. Increase in $A$ (equivalently decrease in $r_A$ or reduction in BW) for the ‘clean’ system Fig1 (a) increases the CO melting temperatures and the switching fields $h_{CO}^\pm$.

For a range of $r_A$ 1.36-1.32, while there is an increase in $T_{CO}$ and $h_{CO}^\pm$, the corresponding quantities in the disordered case initially rise a bit and then is very strongly suppressed and drops to zero at $r_A \sim 1.32$, which corresponds to Sr\textsubscript{0.5}MnO\textsubscript{3}. For materials with larger disorder such as the Ba family, the CO state does not exist even at $h = 0$\textsuperscript{[9]}

While these measurements probe the bulk effects of disorder, recent experiments have also probed\textsuperscript{[10]111314} the effects of disorder on the spatial nature of the melting phenomenon. In particular (Chaddah et al. in their work\textsuperscript{[13]}), Fig.2(a) show that even in the weak disorder samples there is marked non-equilibrium phase coexistence. Here samples of La\textsubscript{0.5}Ca\textsubscript{0.5}MnO\textsubscript{3} are field cooled from 320K to 5K at different fields. The sample cooled in higher field has greater fraction of FM-M regions coexisting with AF-I regions. However, as shown, for the 6T field cooled sample, a small increase in temperature to about 80K, after isothermally reducing the applied field to 1T (at 5K), makes the system lose this FM volume fraction. Infact, the magnetization drops to that of the 1 Tesla field cooled sample at the same temperature. While magnetization by itself is not a good probe of amount of FM regions (which domains can be misaligned), the corresponding resistivity shown in Fig.2.(b), too show an increase in the resistivity for the (6 Tesla)
Here, $c$ and $c^\dagger$ are annihilation and creation operators for $e_g$ electrons and $\alpha$, $\beta$ are the two Mn-$e_g$ orbitals $d_{x^2-y^2}$ and $d_{3z^2-r^2}$, labelled (a) and (b) in what follows, $t_{ij}^{\alpha\beta}$ are hopping amplitudes between nearest-neighbor sites with the symmetry dictated form: $t_{aa}^{\alpha\beta} = t_n^{\alpha\beta} \equiv t$, $t_{bb}^{\alpha\beta} = t\beta_b$ $\equiv$ $t/3$, $t_{ab}^{\alpha\beta} = t_{ba}^{\alpha\beta} \equiv -t/\sqrt{3}$, $t_{cb}^{\alpha\beta} = t_{bc}^{\alpha\beta} \equiv t/\sqrt{5}$, where $x$ and $y$ are spatial directions We consider effectively a lattice of Mn ions and treat the alloy disorder due to cationic substitution as a random potential $\epsilon_i$ at the Mn site picked from the distribution $P(\epsilon) = 1/2(\delta(\epsilon_i - \Delta) + \delta(\epsilon_i + \Delta))$.

The $e_g$ electron spin is $\sigma_i^\mu = \sum_{\alpha} c_{i\alpha\sigma}^\dagger \Gamma_{\alpha\beta}^{\mu} c_{i\beta\sigma}$, where the $\Gamma$’s are Pauli matrices. It is coupled to the $t_{2g}$ spin $S_i$ via the Hund’s coupling $J_H$, and we assume $J_H/t \gg 1$. $\lambda$ is the coupling between the JT distortion $Q_i = (Q_{ix}, Q_{iy}, Q_{iz})$ and the orbital pseudospin $\tau_i^{\mu} = \sum_{\sigma} c_{i\alpha\sigma}^\dagger \Gamma_{\alpha\beta}^{\mu} c_{i\beta\sigma}$, and $K$ is the lattice stiffness. We set $t = 1$, $K = 1$, and treat the $Q_i$ and $S_i$ as classical variables. The chemical potential $\mu$ is adjusted so that the electron density remains $n = 1/2$ which is also $x = 1 - n = 1/2$. Note that this modelling of disorder as random fluctuating potentials is based on the fact the while hopping disorder is crucial to the formation of spin-glass phases, it is onsite disorder rather than hopping disorder that plays the dominant role in the kind of physics we are interested in.

B. Method

We employ a real space exact diagonalization (ED) based Monte Carlo (MC) technique that allows us to perform calculations on system sizes of up to $40^2$. Details are given in.[22] Typically results are averaged over 20-30 disorder realizations.

C. Physical quantities

In order to study the evolution of the system with applied magnetic field we track various physical quantities in real space and momentum space. We compute the ‘one point’ distribution of lattice distortions, $P(Q) = \sum_i \delta(Q - Q_i)$, where $Q_i = |Q_i|$, spatial $Q_i$, $Q_j$ correlations, $DQ(q) = \sum_{ij}(Q_i Q_j) e^{iQ(q)(r_i - r_j)}$, and spin-spin correlations, $S(q) = \sum_{ij}(S_i S_j) e^{iQ(q)(r_i - r_j)}$. Angular brackets represent a thermal average. We also compute the volume fraction of the charge ordered region in the lattice from direct spatial snapshots of the charge distribution. To measure the volume fraction, we tag a site with a particular color if the site has $n > 0.5$ and is surrounded by the four nearest neighbor sites with $n < 0.5$ and vice versa (i.e. a site with local anti-ferro-charge correlation is marked with a particular color). Similarly, if the difference between the charge density at a site with its nearest neighbours is less than a threshold, that site is tagged by a different color, i.e., the charge uniform regions are marked by this color. For intermediate cases, we use an interpolative colour scheme.
The volume fraction is necessary for studying inhomogeneous melting where the momentum space structure factors are not a good measure of the amount of CO in the system. Further, the spatial snapshots of the real space charge density also directly provide visual information on the melting process. While the indicators above measure the spatial correlations and spatial evolution, the metallic or insulating character is tracked via (low frequency) conductivity, $\sigma_{dc}$, and the density of states (DOS), $N(\omega) = \langle \frac{1}{\mathcal{V}} \sum_n \delta(\omega - \epsilon_n) \rangle$, where $\epsilon_n$ are the electronic eigenvalues in some MC background and the angular brackets indicate thermal average. We track all the above quantities as a function of temperature and applied magnetic fields for studying the CO melting phenomenon. Results are disorder averaged over 15-20 distinct disorder realizations.

IV. RESULTS

We begin by looking at the effects of disorder without any applied field. We will then look at the combined effects of both disorder and magnetic fields and discuss the fate of the charge-orbital-spin ordered state.

A. Zero field

We first look at the zero field disorder effects on the charge ordered state by cooling the system in zero field at different disorder strengths for various values of electron-phonon coupling ($\lambda$). Our goal here is to probe the effects of disorder on the charge ordered state using bulk indicators like the volume of the CO state ($V_{CO}$) indicating the extent of the CO in the ground state, the charge order structure factor, giving the coherence of the CO regions and analysis of spatial snapshots of the charge density fields ($n_i$).

Figure 3 (a) and (b) show the disorder averaged volume fraction of the charge ordered regions in the ground state as a function of disorder strengths for various $\lambda$ values indicated in (a) and the corresponding $\pi, \pi$ charge order structure factors in (b). Both for small $\lambda \sim 1.45$ and for $\lambda \sim 2.0$, the volume fractions of the charge ordered regions decrease rapidly with $\Delta$, the disorder strength, while for intermediate $\lambda \sim 1.6-1.7$, the volume fraction of the CO regions remains robust till $\Delta \sim 0.12$, with the $\lambda = 1.7$ case having its CO volume fraction suppressed slightly more rapidly than that for $\lambda \sim 1.6$ case. The CO structure factor provides a clearer picture of the way disorder destabilizes the CO state. For weak and strong $\lambda$ cases till about $\Delta = 0.1$, while the volume fraction of the CO regions is about 80%, the corresponding structure factors diminish rapidly, indicating formation of domain walls between different CO regions. For the intermediate $\lambda$ case, the system presents a single phase CO state till $\lambda \sim 0.12$, beyond which the $\lambda = 1.7$ case is more prone to losing the CO state than the $\lambda = 1.6$ case. This fact is seen exemplified in the spatial snapshot analysis to which we turn next. Figure 4 shows the snapshots of the CO state ($n_i$) at three values of disorder, from weak, through intermediate, to strong from top to bottom, for the four $\lambda$ values increasing from left to right (see the corresponding caption for the values). Figure 5 shows the snapshots of the corresponding magnetic states.

(i) Small and large $\lambda$ regimes: At small disorder, the low $\lambda$ case (the extreme left column) begins developing metallic regions, which are concomitant with local disruption of the CE chains. With increase in disorder, these metallic regions grow along with appearance of line-like AF states. Further increase of disorder to $\sim 0.15$ leads to formation of distinct FM-M regions. The strong coupling case, which essentially consists of almost site localized electrons with weak overlap with neighbouring sites, starts forming clear domain walls at low and intermediate disorder and finally at large disorder, forms a badly disordered polaronic state. The corresponding magnetic state is initially disrupted by formation of local CE regions of opposite handedness, which at large disorder develops patches with local $\pi, \pi$ magnetic correlations. The small and larger $\lambda$ states under the effect of disorder can be understood in terms of disorder hindering the growth of the ideal CE-CO-I state from the intermediate temperature states. For low $\lambda$, at intermediate temperature and $\Delta = 0$, the system is in a FM-M phase which in absence of disorder gives way to a CE-CO-I state at low temperature. However in the presence of disorder, a fraction of the FM-M phase remains trapped at low temperatures. Similarly, for large $\lambda$ case, since the effective charge order stiffness is small at large $\lambda$ values, the intermediate state is a disordered polaronic phase and it is this state which remains partially trapped due to disorder when the system is cooled to low temperatures.
Since the metallic regions at low T can gain kinetic energy by delocalizing electrons within the regions, double exchange promotes FM order and the system develops FM-M patches, for the low $\lambda$ case. For large $\lambda$ case however, the since the on site localization tendency (which grows as $\lambda^2$) is larger than the gain from kinetic energy, the double exchange is suppressed and antiferromagnetic-superexchange dictates a local ($\pi,\pi$) antiferromagnetic regions existing in a matrix of small CE regions (which exists in regions with local CO).

(ii) Intermediate $\lambda$ regime: Increasing $\lambda$ from weak to intermediate values lead to a deepening of the CE-OO-CO minima in the energy landscape small, where, disorder is unable to trap the system partly in the FM-M phase (which in a Ginzburg-Landau scenario would no longer remain metastable at low temperatures). Similarly decreasing $\lambda$ from strong couplings increases the effective CO stiffness, thus pushing up, in energy, the disordered polaronic phase, which again for weak and intermediate disorder would be unstable at low temperature.

The trend in stability of the CO state with $\lambda$ suggests a possible intermediate $\lambda$ where the CE-OO-CO state is most robust to disorder. This corresponds to $\lambda$ $\sim$ 1.6, for the parameters used in the present work. Results at $\lambda$ = 1.7 are specifically shown to demonstrate the weakening of the CO state compared to $\lambda$ = 1.6.

(iii) $\lambda$–$\Delta$ phase diagram: Fig.6.(a) shows the variation of $T_{CO}$ with $\Delta$ at various $\lambda$. 6.(b) shows the $\lambda$–$\Delta$ phase diagram. In Fig.6.(a), the low disorder $T_{CO}$ increases with increasing $\lambda$, but for $\Delta$ $\sim$ 0.1, the $T_{CO}$ at larger $\lambda$ starts falling and by $\Delta$ $\sim$ 0.12, goes below those for weaker $\lambda$ values.

To understand this behaviour, we mapped out the the $\lambda$–$\Delta$ phase diagram shown in Fig.6.(b). Since at very low $\lambda$ and $\Delta = 0$, the system is in a FM-M state, at small disorder, this state will be a disordered FM-M. Thus, the CO region in the $\Delta$–$\lambda$ parameter space, on the lower $\lambda$ side is bounded by a FM-M at zero disorder and by a disordered FM-M at intermediate disorder. On the other hand, at large $\lambda$ and zero disorder, the system, at $T$=0 will remain in the CO state at all finite $\lambda$ values (ignoring quantum fluctuations). However, at any finite $T$, small thermal fluctuations will destroy the long range nature of the charge order, although the electrons will be almost site localized. This will happen due to the essential on site localization of the electrons which leads to suppression of the effective charge order stiffness. By the same token, at any finite $\Delta$, there is always a critical $\lambda$, beyond which the system, even at $T$=0, turns into a disordered polaronic state.

The asymptotic limit where $\lambda$ is large enough to allow perturbation in kinetic energy can be analytically handled. Infact this very general disorder induced suppression of long range order is well understood in classical models. For the random field Ising model (RFIM), this has been studied in detail. The real regime where the materials exist, $\lambda$ $\sim$ 1.5–1.7, is non-perturbative and has to be understood as the regime interpolating between the large $\lambda$ asymptote and the small $\lambda$ $< 1.4$ FM-M. This naturally causes, as seen in Fig. 6.(b), the region for stable CO to be finite at any finite value of $\Delta$ and explains why with increasing $\lambda$, the $T_{CO}$ falls more rapidly at finite disorder. Further, the two kinds of CO regions, CD-I and CD-II, in the Fig. 6(b), refer to disordered FM-M and disordered polaronic regime with AF magnetic background. The dashed lines on Fig.6 (b) represents parameter points along which calculations were done. We shall later use the $\lambda$–$\Delta$ phase diagram to explain experimental observations on the material systematics of the critical melting fields.
FIG. 6: Colour online: (a) The variation of $T_{CO}$ with disorder strength $\Delta$, at various electron-phonon couplings. (b) The $\lambda - \Delta$ phase diagram. Note, the charge disordered regions at weak $\lambda < 1.45$ is very different from that which occurs at larger $\lambda > 2$. The weaker $\lambda$ charge disordered phase has uniform charge density and the system is a ferromagnetic metal. At large $\lambda$, the system is essentially site localized and the nearest neighbour overlap is negligible and the system can lose the charge order under small perturbation and turn into a disordered polaronic state.

B. Disorder induced rounding of first order transition

When a first order phase transition (FOPT) occurs in a disordered background, the transition ceases to be discontinuous and acquires a smooth character. Here we track the magnetic field induced FOPT between the CE-CO-I and the FM-M as it takes place in the disordered background and compare to what we found in the clean case. Fig. 7 and 8 show this evolution of the CO state as we sweep the magnetic field after cooling the system to low temperature. While Fig. 7 tracks measures of bulk properties $V_{CO}$, $S_{fm}$ and $\rho$, as a function of applied field in the clean (a), (c) and disordered (b),(d) cases, Fig. 8 looks at the actual spatial profile of the CO melting. The spatial profile in Fig. 8, for the clean system (top panel) is seen to resist the field up to $h/t = 0.06$, beyond which it abruptly goes to a percolative FM-M state. The disordered case (bottom panel) shows a more gradual trend in the melting, it starts by creating small metallic regions which grow over a window of field values to reach the final percolative metallic state. This gradual loss of CO volume fraction is corroborated by Fig. 7(b) and the abruptness of the transition on the clean case is correlated with Fig. 7(a). The fact the the systems are metallic is seen from the resistivities shown in Fig. 7(c) and (d) which follow the abruptness of the change in $V_{CO}$ in the clean case and smoothened change in disordered case.

C. Field melting & the relation to the $\lambda - \Delta$ phase diagram

Here we look at the detailed behaviour of the thermal and magnetic melting scales for the CO state with $\lambda$ and disorder. Since it would also help making comparison with experiments, we restate the broad experimental results. While for the systems with $\sigma_A \sim 10^{-3} A^2$ (e.g. the Ca family), the magnetic melting scales increase with decreasing $r_A$, for systems with $\sigma_A \sim 10^{-2} A^2$ (e.g. the Sr family), the melting scales initially increases with decreasing $r_A$ and then are strongly suppressed and eventually go to zero with further decrease in $r_A$. These are shown in Fig.1(a) and 1.(b).

We follow the same $h,T$ protocols as in the experiments, i.e, we sweep up and down in $h$ at low $T$ after cooling at $h = 0$. In terms of the numerics we start from zero field and then first increase the magnetic field up to $h/t \sim 0.2$ and then reduce to zero in steps of 0.01. As discussed earlier, the forward melting field is defined as $h_{+}^{CO}$ and that in the downward sweep is $h_{-}^{CO}$. Fig.9(a)-(d) show the results of our calculation starting with $\Delta/t = 0$ in (a) to strong disorder $\Delta \sim 0.12$ in (d). We clearly see that apart from the expected overall suppression in melting scales with disorder, there is a gradual
FIG. 8: Colour online: The spatial snapshots of charge densities for zero field cooled samples, which are then subjected to a sweep in the magnetic field at low temperature for clean (Top panel) and disordered($\Delta/t = 0.12$) (Bottom panel). The snapshots are shown for field values ($h/t=0.04,0.05,0.06,0.07,0.08,0.09$) from left to right, for the increasing part of the field cycle. The corresponding CO volume fractions are shown in Fig.7(a) and (b). Clearly, in the clean case, the CO remains stable up to $h/t \sim 0.06$ and then collapses within a window of $\Delta(h/t) = 0.01$ to a state with about 30% CO regions and 70% FM-M. The disordered case however, starts losing CO at $h/t = 0.05$ and collapses, within a window of $\Delta(h/t) = 0.04$ into a percolative metallic state with roughly similar composition as in the clean case.

downturn with increasing $\lambda$ (or decreasing $r_A$). In (a) the melting field diverges, i.e., the CO state is stable without CE order. In (b) the melting scales become finite in the same $\lambda$ regime and begin to get strongly suppressed in (c) and (d).

To explain the results we refer back to Fig.6(b), the $\lambda - \Delta$ phase diagram. Here we have marked by the red dashed lines the ($\lambda,\Delta$) combinations for which we have shown results in Fig.9(a)-(d) with progressive increase in the values of disorder from a to d). From Fig 6(b) it is clear that while at $\Delta = 0$, the system has only one boundary with the CD-1 region, so the melting scales are the smallest at $\lambda \sim 1.45$ and increase with increasing $\lambda$. For all other dashed lines the systems encounter boundaries with CD-1 and CD-2, so there is a generic suppression in the magnetic and thermal melting scales. Thus the presence of disorder causes a competition between the long range order of the CO state and random pinning effects of disorder which weakens the effecting CO stiffness and hence the melting temperatures and melting field.\[21\]

D. Disorder induced trapping of metastable states

We now briefly turn to certain aspects of disorder induced coexistence in the half doped manganites The experimental results as discussed in Section II have three major aspects, one the disorder induced trapping of metastable phase in the low temperature state of the system, two, the non-equilibrium nature of such coexistent states and three, the strong protocol dependence of the phase fractions. Here we present our results only on the first aspect, while we will report the remaining two in a later work.

The results shown in Fig. 10 are obtained by cooling the systems in presence of various fixed magnetic fields at different disorder strengths. All results are on $16^2$ systems and the results are averaged over many disorder realizations. We use two indicators for the study, one, is the volume faction of the CO regions($V_{CO}$) and the other is the measure of excess number of FM bonds in the system over that which exists in the CE phase ($\Delta V_{FM}$). In the CE phase, each site in the plane has four bonds two of which are ferromagnetic and two antiferromagnetic. Thus if we define $\Delta V_{FM} = \frac{N_{FM}^{} - N_{FM}^{CE}}{N_{CE}}$, then in the CE phase $\Delta V_{FM} = 0$, in the FM phase it is 1 and is negative if the number of bonds antiferromagnetic bonds are more than the number of ferromagnetic bonds. In the case of G-type AF phase it is -1. Although $\Delta V_{FM}$ cannot distinguish between two spatial patterns with the same number of AF and FM bonds, it is a useful measure of net FM volume on the system and in the present definition gives the net increase or decrease in the FM volume fraction from that which exists in the CE phase.
are the largest and are given as an estimate of the maximum error in the numerics.

$\lambda$ increasing the strength of disorder $\Delta$ not only suppresses the overall melting scales, but also changes the respective. While for $\Delta = 0$, the melting fields diverge beyond a critical $\lambda$ and the $T_{CO}$ grows, in the shown $\lambda$ window, increasing disorder causes a gradual downturn in all the melting scales at weak disorder and finally strongly suppresses these scales at strong disorder $\Delta \sim 0.12$. Error bars for the strong disorder case (d) are the largest and are given as an estimate of the maximum error in the numerics.

Effects of magnetic field in a clean systems: We begin by looking at the effect of magnetic field on $V_{CO}$ when there is no disorder in the system. Fig. 10(a) shows the variation of $V_{CO}$ with applied magnetic fields, at three $\lambda$ values. It was shown in\textsuperscript{22} that the system at half doping phase separates, at finite magnetic fields, into ‘FM-M AF-M’ at low $\lambda$ and between ‘FM-CO AF-M’ at $\lambda \geq 1.6$. Here we see that for $\lambda < 1.6$ the system at low fields ($h \sim 0.02 - 0.04$), actually lose almost all the CO regions to a FM-M regions and then regain a certain volume fraction of the CO state at intermediate field values. For $\lambda \geq 1.6$, the system directly goes into a phase separated state, without the low field FM-M phase. Fig. 10(c) shows $\Delta V_{FM}$, for low fields, for $\lambda = 1.5$. For $h \sim 0 - 0.01$, the system resists any significant change in the CE phase. At $h = 0.012$, it converts about 10% of the AF bonds to FM bonds. Further increase of field makes the system lose more AF bonds. However, we will restrict our attention to $h \leq 0.01$ and look at the effects of disorder on the CE phase.

Interplay of magnetic field and disorder: Fig. 10(b) shows $V_{CO}$ as a function of magnetic field at two disorder values for a typical low $\lambda = 1.5$ case. While beyond $h = 0.05$, the phase separation tendency masks the disorder effects, we focus our attention to low field. For $h \leq 0.05$, we see that while for those field values where the clean system is in the CO state, increasing $\Delta$ reduces the volume fraction of the CO regions and for those values of $h$ where the clean system would be a FM-M, disorder traps some fraction of the system in the CO state. This clearly shows the generic effect of disorder assisted trapping of the nearby (in energy) metastable phases in the low temperature state of the system. Fig. 10(d) shows the variation of $\Delta V_{FM}$ with disorder at various magnetic field values. At very low fields $h = 0.002$, the system presents no change to the CE phase when there is no disorder, however, in the presence of disorder, the ground

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**FIG. 9:** Colour online: (a) to (d) show the variation of the disorder averaged $T_{CO}$, $h_{CO}^+$ and $h_{CO}^-$ for $\Delta = 0, 0.06, 0.1, 0.12$ respectively. While for $\Delta = 0$, the melting fields diverge beyond a critical $\lambda$ and the $T_{CO}$ grows, in the shown $\lambda$ window, increasing the strength of disorder $\Delta$ not only suppresses the overall melting scales, but also changes the $\lambda$ (or $r_A$) dependence qualitatively. Within the same $\lambda$ window, increasing disorder causes a gradual downturn in all the melting scales at weak disorder and finally strongly suppresses these scales at strong disorder $\Delta \sim 0.12$. Error bars for the strong disorder case (d) are the largest and are given as an estimate of the maximum error in the numerics.

**FIG. 10:** Colour online: (a) The evolution of CO volume fraction with $h$ for ranging $\lambda$. The finite $V_{CO}$ at $h \sim 0.05$ and beyond is due to PS at intermediate magnetic fields. For lower $\lambda$ the system loses most of $V_{CO}$ at low fields before PS into FM-M, FM-CO and AF-M. For $\lambda \sim 1.6$, the system directly PS between AF-M and FM-CO at $h \sim 0.05$, without the occurrence of the low field FM-M state. (b) The effect of disorder on $V_{CO}$. Results are for $\lambda = 1.5$ and $\Delta = 0.05, 0.16$. When compared to $\Delta = 0$ (dashed line), increasing disorder, at low $h$, leads to larger $V_{CO}$. At larger $h$, however, this effect is masked by the field induced PS. (c) The weak field response of the the magnetic ground state at $\Delta = 0$. For $h \leq 0.012$, the system remains in the CE state. Beyond this within a $\Delta h \sim 0.002$, the system loses about 10% of the antiferromagnetic bonds to ferromagnetic ones. (see text for a definition of $\Delta V_{FM}$). (d) Remaining at $h < 0.012$, where the clean ground state is CE-CO-I, this shows the trapping of the higher temperature FM with increasing disorder. Results are shown for three cooling fields.
state has a certain volume fraction of FM region and this fraction grow to about 5% as the disorder strength $\Delta$ grows from 0 to 0.2. At larger $\Delta \sim 0.3$ the system does not have any clear order due to strong random pinning effects of disorder. Further, increasing magnetic field and disorder allows one to achieve a continuum of values for $\Delta V_{FM}$, which together with the results in Fig. 10(b), shows the tunability of the CE-CO and FM-M volume fractions by cooling in different applied fields.

V. CONCLUSIONS

Using a real space Monte-Carlo scheme we have shown how the charge ordered state in the half-doped manganites is affected by the presence of disorder and an applied magnetic field. We illustrated the disorder induced broadening of the melting transition and mapped out the full $h-T$ phase diagram for various combinations of bandwidth and disorder. We could explain the counterintuitive bandwidth dependence seen in the Sr based manganites. We motivated the trends seen in the detailed numerical results by analysing the stability of the $h=0$ charge ordered state in response to disorder. Finally, we observe that disorder leads to trapping of metastable phases in the low temperature state. Different field cooling pathways will trap different amounts of FM-M in the nominal ‘CE-CO-I’ ground state.

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