

Universal probes for antiferromagnetic correlations and entropy in cold fermions on optical lattices

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(Dated: December 20, 2011)

We determine short-range antiferromagnetic (AF) signatures in the half-filled Hubbard model at strong coupling using dynamical mean-field theory and numerically exact methods for a cubic lattice and at lower dimensionality. Upon cooling, the transition from the charge-excitation regime to the AF Heisenberg regime is signaled by a universal minimum of the double occupancy at entropy $S/(Nk_B) \approx \log(2)$ per particle and a rapid linear increase of the next-nearest neighbor (NNN) spin correlation function below. This crossover, driven by a gain in kinetic exchange energy, appears as the essential AF physics relevant for current cold-atom experiments. In larger systems, the detection of long-range AF order requires measurements of spin correlations at NNN (or longer) distances.

PACS numbers: 67.85.-d, 03.75.Ss, 71.10.Fd, 75.10.-b

Materials with strong electronic correlations are, due to their increasing technological importance, e.g., in magnetoresistive and superconducting devices, a prime subject of current research [1, 2]. Theoretical investigations of corresponding Hubbard type models have shed light on many strong-coupling phenomena including metal-insulator transitions, non-Fermi-liquid behavior, and various types of magnetic and orbital order [3]. However, important questions remain, most notably regarding high-temperature superconductivity, for which so far no mechanism could be established. Recently, a novel class of correlated Fermi systems, namely ultracold fermionic atoms (such as ⁴⁰K and ⁶Li) on optical lattices, has opened a new promising direction of research: cold atoms are predicted to serve as *quantum simulators* for the Hubbard type solid-state Hamiltonians of interest [4–6].

Indeed, the Mott metal-insulator transition was recently demonstrated in two-flavor mixtures of ⁴⁰K on cubic optical lattices by experimental observation and quantitative theoretical analysis of signatures in the compressibility [7] and in the double occupancy [8]. This success established that the single-band Hubbard model

$$\hat{H} = -t \sum_{\langle ij \rangle, \sigma} \hat{c}_{i\sigma}^\dagger \hat{c}_{j\sigma} + U \sum_i \hat{n}_{i\uparrow} \hat{n}_{i\downarrow} \quad (1)$$

(with hopping amplitude t , on-site interaction U , and $\hat{n}_{i\sigma} = \hat{c}_{i\sigma}^\dagger \hat{c}_{i\sigma}$) can be realized to a reasonable accuracy using ultracold fermions in the interesting interaction range, which certainly supports the hopes of accessing also less understood Hubbard physics in similar ways.

However, all attempts of realizing and detecting *quantum magnetism* in cold lattice fermions have failed so far. In fact, it has not even been possible yet to verify specific signatures of antiferromagnetic (AF) correlations which are ubiquitous in correlated electrons and believed to play an important role in high-temperature superconductivity.

This type of physics clearly has to be under control before cold fermions can really play a useful role as *quantum simulators*. Up to now the failures to detect AF signals have primarily been attributed to cooling issues [9, 10]. Indeed, the coldest systems achieved so far have central entropies per particle of $s \equiv S/(Nk_B) \approx \log(2) \approx 0.69$ [11] while AF long-range order (LRO) on a cubic lattice is expected only for entropies $s < s_N \approx 0.34$ [10, 12, 13].

We will argue in the following that this discrepancy, by a factor of 2, is *not* the primary issue for current AF related cold-atom experiments, which extract information about the nearest-neighbor (NN) spin correlation function $\langle \hat{\sigma}_i \cdot \hat{\sigma}_j \rangle$ (for Pauli matrices $\hat{\sigma}$) from modulation spectroscopy measurements [10, 14] or a superlattice approach [15]. While this observable should, in principle, reveal the Néel transition at least in the Heisenberg limit (where it corresponds to the energy), already the role of the entropy as the relevant thermodynamic variable in the cold-atom context makes this route impractical, with overly subtle features in $\langle \hat{\sigma}_i \cdot \hat{\sigma}_j \rangle(s)$ at s_N even in the thermodynamic limit (cf. Fig. 4). Even worse signals are to be expected in the finite and inhomogeneous systems realized in fermionic experiments, with a shortest experimental length scale of about 10 lattice spacings [17], for which the concept of LRO appears of limited value.

Accepting that true LRO, defined by the infinite-distance limit of spin correlations, is not directly relevant for cold atoms, one may ask: (i) is there a threshold distance beyond which spin correlations have “long-range characteristics” (in a sense to be specified) and (ii) can we define “short-range antiferromagnetism” as a unique scenario with universal properties, appearing only in a certain entropy range? The answer to both questions is “yes”: quite interesting AF correlation physics emerges at entropies $s \lesssim \log(2)$, i.e. in reach of current cooling techniques. Since, in addition, the threshold distance

turns out to be rather small (but larger than one lattice spacing), our quantitative predictions should enable experimentalists to verify specific AF signatures with current system sizes and, thereby, to get the long-sought grip on *quantum magnetism*.

In the following, we will first discuss an enhancement of the double occupancy D (i.e. also of the interaction energy DU) at low temperatures T which has previously been proposed as an AF signature on the basis of dynamical mean-field theory (DMFT) [19]. New DMFT results for a half-filled system at moderately strong coupling $U/t = 15$ will be compared with numerically exact determinantal quantum Monte Carlo (DQMC) data on a cubic lattice. The analysis of DMFT artifacts, characteristic of its infinite-dimensional character, will be extended to the full dimensional range based on DQMC and Bethe ansatz (BA) results in dimensions $d = 2$ and $d = 1$. In addition to $D(T)$, we obtain high-precision estimates of the entropy $s(T)$ in all cases, enabling us to switch to the relevant entropy picture. We observe an asymptotic collapse in $D(s)$ as a function of dimensionality, with a universal minimum at $s \approx \log(2)$ and no significant features at s_N in the cubic case. We then, explore the short-range AF physics in more detail, showing also kinetic and total energy as well as spin correlation functions at various distances. Additional insight will be gained from stochastic series expansion (SSE) results for the Heisenberg model.

AF signatures in the double occupancy – Signatures in D have previously been linked to antiferromagnetism within dynamical mean-field theory (DMFT). According to DMFT, the low-temperature formation of an AF core in a fermionic cloud on an optical lattice (with central filling $n = 1$) is signaled, at strong coupling, by a distinct enhancement of D in the same region. The absolute increase of D is largest for $U/t \approx 12$; it should be detectable even in experiments integrating over the whole cloud [19]. It is, however, clear that not all aspects of the DMFT scenario are realistic: after all, DMFT overestimates the Néel temperature by up to 30% in the simple cubic case [28, 29]. Thus, sharp signatures in $D(T)$ (cf. Fig. 1a) cannot remain at T_N^{DMFT} (except for the weak-coupling regime $U/t \lesssim 6$). But what is, precisely, the impact of finite dimensionality?

Impact of dimensionality – In order to gain more insight into these issues, DMFT and QMC data for the cubic lattice are compared at $U/t = 15$ with QMC results for the square lattice and BA solutions of the infinite chain at equivalent [32] interactions in Fig. 1a. Here, the DMFT data (circles) can also be interpreted as an exact result in infinite dimensions. After rescaling [32], we find rapid convergence with increasing dimensionality at high T and generally similar shapes of $D(T)$ for $1 \leq d \leq \infty$. Still, $d \gg 3$ would apparently be needed in order to converge to the DMFT results also at T_N^{DMFT} . Furthermore, the minimum in $D(T)$ occurs at or above twice T_N^{DMFT}

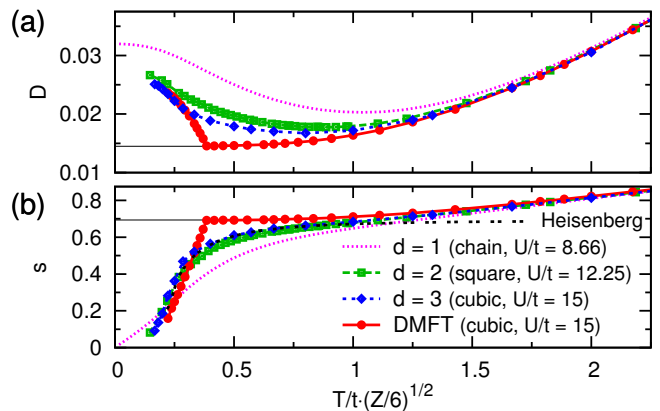


FIG. 1. (Color online) Hypercubic lattice ($1 \leq d \leq 3$) at strong coupling $U/(\sqrt{Z}t) \approx 6$: a) Double occupancy $D(T)$ as estimated from DMFT ($d = 3$, circles), DQMC ($d = 3$: diamonds, $d = 3$: squares), and BA ($d = 1$, dotted line). b) Corresponding estimates of entropy per particle $s = S/(Nk_B)$.

in dimensions $1 \leq d \leq 3$.

On the other hand, not temperature T , but the entropy s is the experimentally relevant control parameter. Fig. 1b shows numerically exact data for $s(T)$, obtained directly for $d = 1$, and via the thermodynamic relation (valid for $n = 1$)

$$S(\beta) = \log(4) + \beta E(\beta) - \int_0^\beta d\beta' E(\beta')$$

(with $\beta = 1/(k_B T)$ and energy E) for $d = 2, 3$ and DMFT. The agreement between $d = 2$ and $d = 3$ is striking; the latter results converge to the Heisenberg limit for $T \lesssim 0.8t$. Remarkably, the AF DMFT solution (circles for $T < T_N^{\text{DMFT}}$) recovers the QMC results for the cubic lattice (diamonds) at $T \lesssim T_N \approx 0.25t$. This shows that the previously criticized [22] saturation of nonmagnetic solutions (dotted line) at $\log(2)$ for $T \rightarrow 0$ is an artifact of the phase restriction, not of DMFT itself. [too much?]

In Fig. 2 we present the experimentally relevant curves $D(s)$, obtained by combining the data of both panels of Fig. 1. While the overall general agreement between the data sets and the regular dimensional convergence at both high and low s already appear striking, our study reveals an important physical fact not realized so far: the minimum in D (at strong coupling) corresponds to $s \approx \log(2) = s_N^{\text{DMFT}}$ in all dimensions, down to $d = 1$. *A posteriori*, this behavior is easy to understand: $s < \log(2)$ is only possible for a two-flavor system at $n = 1$ by spin coherence, i.e. the development of (possibly short ranged) AF correlations; these, in turn, enhance D [19]. A practical consequence of our finding is that, contrary to earlier expectation, cooling to $s < \log(2)$ will give experimental access to AF physics in any dimension at strong coupling; $s < \log(2)/2$ is not needed.

More generally, the evolution of D is a near-perfect thermometer for ultracold atoms measuring AF corre-

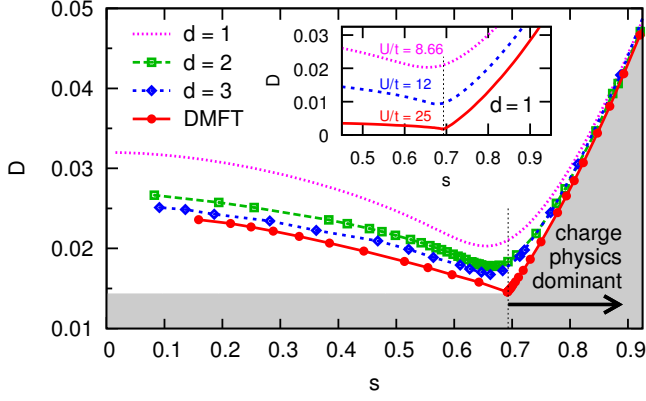


FIG. 2. (Color online) Hypercubic lattice at strong coupling: Double occupancy versus entropy. In all cases, the minimum of the double occupancy corresponds to $s \approx \log(2)$ (dotted line). The shaded area indicates the nonmagnetic contribution to D . Inset: $D(s)$ in $d = 1$ for various interactions.

lations and (in $d = 3$) the proximity to AF LRO. In fact, any positive deviation of $D(s)$ from the nonmagnetic background (shaded in Fig. 2) should be linked to AF correlations, generalizing Takahashi's ground state expression [18]

$$D_0 = \frac{Zt^2}{2U^2} (1 - \langle \hat{\sigma}_i \cdot \hat{\sigma}_j \rangle_0) + \mathcal{O}\left(\frac{t^4}{U^4}\right). \quad (2)$$

Here, $\langle \hat{\sigma}_i \cdot \hat{\sigma}_j \rangle_0$ is the nearest-neighbor correlation in the quantum Heisenberg model (at $T = 0$): $\langle \hat{\sigma}_i \cdot \hat{\sigma}_j \rangle_0 = -1.00$ ($d = \infty$, Weiss MF); -1.20 ($d = 3$) [33]; -1.34 ($d = 2$) [34, 35]; -1.77 ($d = 1$) [18], which is stronger in lower d , consistent with our finite- T results. Thus, irrespective of the measurement technique, signatures of AF correlations may be easier to detect experimentally (at fixed s) for lower (effective) dimensionality. Conversely, a tuning of the hopping amplitude in z direction could help to discriminate magnetic effects from those of charge excitations; similar ideas including frustration will be explored in a separate publication [36].

Although going beyond the strong coupling regime may, from the first sight, seem favourable due to the higher values of D , it does not bring any real advantages. The AF features are less pronounced in double occupancy, as well as in other local observables (i.e. in total or kinetic energy, spin correlations). Moreover, decreasing the onsite interaction beyond $U/(\sqrt{Z}t) \lesssim 4$ reduce the critical entropy.

AF signatures in other observables – As we just demonstrated above, in the strong coupling regime the onset of local antiferromagnetism is signaled by the minimum in double occupancy at $s \approx s_N^{\text{DMFT}} = \log(2)$. Corresponding signatures appear also in other local observables. So, the kinetic energy E_{kin} in $d = 1$ exhibit shoulder at $s \approx s_N^{\text{DMFT}}$, which transforms into the maximum with increasing the dimensionality, see Fig. 3a. The to-

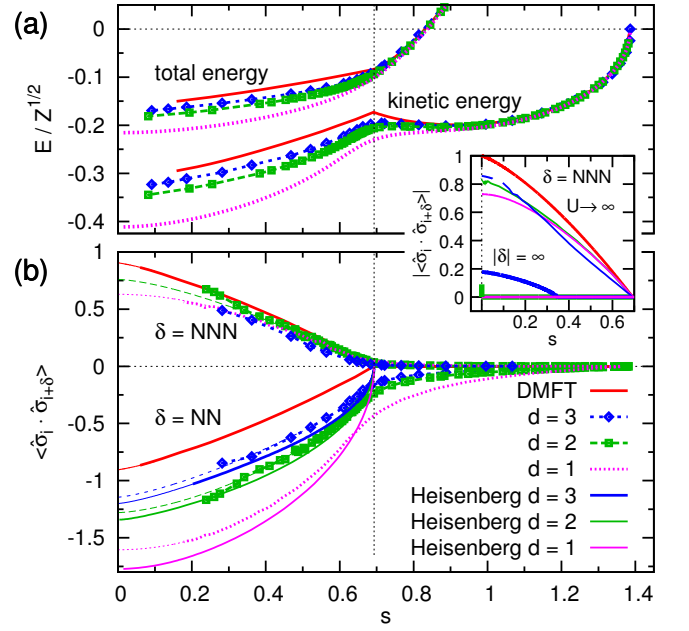


FIG. 3. (Color online) Hypercubic lattice at strong coupling: a) Rescaled total and kinetic energy versus entropy. b) Spin correlations $\langle \hat{\sigma}_i \cdot \hat{\sigma}_{i+\delta} \rangle$ between nearest neighbours [$\delta_{d=1} = 1$, $\delta_{d=2} = (1, 0)$, $\delta_{d=3} = (1, 0, 0)$] and between next-nearest neighbours [$\delta_{d=1} = 2$, $\delta_{d=2} = (1, 1)$, $\delta_{d=3} = (1, 1, 0)$]. Inset: next-nearest neighbours and infinite-range spin correlations for the Heisenberg model.

tal energy $E = E_{kin} + UD$ being a monotonous function of entropy shows a kink in this entropy interval. Neither the total energy, nor its kinetic and potential components reveal any visible signature at the Néel phase transition $s_N = \log(2)/2$ in $d = 3$. Although this could be attributed to the finite-size effects or numerical noise in DQMC calculations, the main begetter here is the entropy representation. Indeed, it is easy to show that peaks in specific heat, as appear due to the phase transitions, are heavily suppressed and smoothed when energy is considered as a function of entropy. Our "local probes for local order" conclusion is also supported by the recent experimental observation, that even as a function of temperature local properties are unaffected by magnetic phase transition [41].

Spin correlation functions, and especially the one between the nearest neighbors (NN), are probably the most discussed observables in the context of experimental detection of AF in lattice fermions [10, 14, 15, 40]. The NN spin correlation function appears also as a natural choice from the perspective of the Heisenberg model, describing the relevant spin physics in the strong coupling limit. However, if the onsite interaction is strong-but-finite, NN spin correlation function possess strong high-entropy tails for all finite dimensions d , see Fig. 3b. It does not provide any specific signal, neither by the onset of local spin order at $s_N^{\text{DMFT}} = \log(2)$ nor at the Néel critical entropy in

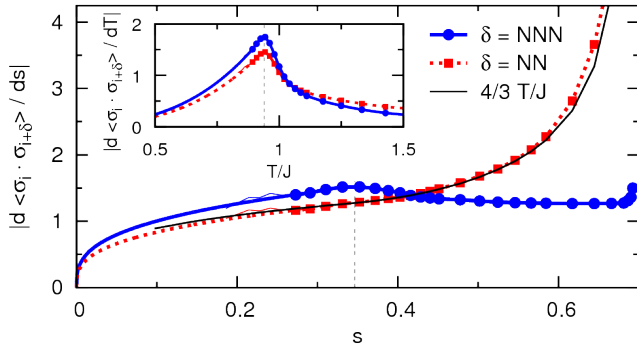


FIG. 4. (Color online) First entropy (main panel) and temperature (inset) derivative of the NN and NNN spin correlation functions of the Heisenberg model in $d = 3$.

three dimensions $s_N = \log(2)/2$. Therefore it is rather of minor usefulness as an experimental observable to monitor the onset of AF.

It is clear, that the only explicit indication of AF LRO may come from the infinite-range spin correlations, as shown on the inset of Fig. 3 (for the Heisenberg model). However, the experimental relevance of this signal and of the LRO itself is not obvious on the length scale of the experimentally realized systems. Moreover, the decrease of the central entropy per particle by factor of 3 to 4 respective to the current state-of-art will be required for a detectable signal in $d = 3$, lower dimensions will give no signal at all.

The opposite dimensional tendencies in these two limiting cases (NN vs. LRO) forced us to look in detail the "intermediate" range. And indeed, already the spin correlations between the next-nearest neighbors (NNN) provide the perfect signal of the local AF: with the dimension-independent onset at $s \approx s_N^{\text{DMFT}}$ and the absence of high-entropy tails. The entropy dependence of NNN spin correlations is shown in Fig. 3b for the Hubbard model at strong coupling $U/(\sqrt{Z}t) \approx 6$, and on the inset of Fig. 3 for Heisenberg model.

The detailed analysis of spin correlations for the Heisenberg model in $d = 3$, see Fig. 4...

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