Exploring the ferromagnetic behaviour of a repulsive Fermi gas through spin dynamics

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Ferromagnetism is a manifestation of strong repulsive interactions between itinerant fermions in condensed matter. Whether short-ranged repulsion alone is sufficient to stabilize ferromagnetic correlations in the absence of other effects, such as peculiar band dispersions or orbital couplings, is, however, unclear. Here, we investigate ferromagnetism in the minimal framework of an ultracold Fermi gas with short-range repulsive interactions tuned via a Feshbach resonance. Whereas fermion pairing characterizes the ground state, our experiments provide signatures suggestive of a metastable Stoner-like ferromagnetic phase supported by strong repulsion in excited scattering states. We probe the collective spin response of a two-spin mixture engineered in a magnetic domain-wall-like configuration, and reveal a substantial increase of spin susceptibility while approaching a critical repulsion strength. Beyond this value, we observe the emergence of a time window of domain immiscibility, indicating the metastability of the initial ferromagnetic state. Our findings establish an important connection between dynamical and equilibrium properties of strongly correlated Fermi gases, pointing to the existence of a ferromagnetic instability.

The magnetic properties of a variety of quantum systems, ranging from electrons in transition metals1,2 and normal 3He liquids3 to neutron and quark matter within the crust of neutron stars4,5, emerge from strong interactions between itinerant fermions—that is, not localized into a crystal lattice. Itinerant ferromagnetism can be intuitively captured by Stoner’s simple mean-field framework: a free electron gas can become ferromagnetic once a short-range screened Coulomb repulsion between oppositely oriented electron spins overcomes the effect of Fermi pressure, which would favour a spin-disordered paramagnetic state. A sufficiently strong repulsion promotes the parallel alignment of magnetic moments, at the price of an increased kinetic energy, making the paramagnetic state unstable towards a ferromagnetic one. Stoner’s picture enables one to qualitatively describe the phase diagrams of many-electron systems. However, various effects beyond short-range repulsion are thought to promote or suppress ferromagnetism in solids1,2. In particular, there exist materials where a Stoner-type instability of the repulsive Fermi liquid state is altered by competing mechanisms. Notable examples are the emergence of unconventional superconductivity adjoining ferromagnetism in intermetallic compounds7 and the non-Fermi liquid behaviour of the paramagnetic state in itinerant-electron ferromagnets8.

Paradoxically, even the paradigmatic scenario of an ultracold atomic Fermi gas with short-ranged repulsive interactions entails a superfluid ground state of paired fermions, rather than a ferromagnetic one. This stems from the fact that genuine zero-range repulsion, encoded in the s-wave scattering length a, necessarily requires an underlying attractive potential with a weakly bound molecular state9. Hence, the repulsive Fermi gas corresponds to a metastable excited (upper) energy branch of the many-body problem10–12 (see Fig. 1a), intrinsically unstable against pair formation13–15. Although Landau’s Fermi liquid theory approaches and quantum Monte Carlo (QMC) calculations16–21, intentionally neglecting pairing, confirm Stoner’s ferromagnetism of a homogeneous Fermi gas driven only by short-range repulsion, experiments with ultracold repulsive Fermi gases have been inconclusive thus far. Studies of spin mixtures prepared in the paramagnetic phase and quenched to strong repulsion12–22 found inelastic decay processes to be rapid with respect to the development of magnetic domains13, concluding that the system cannot undergo a ferromagnetic phase transition11,12. On the other hand, recent spectroscopic experiments22 of highly imbalanced spin mixtures in the polaronic regime11,12 revealed the Fermi liquid phase to become energetically and thermodynamically unstable beyond a critical repulsion strength, in quantitative agreement with theoretical predictions for polarized repulsive gases23. Together with an unexpectedly long lifetime in the strongly repulsive regime24, this suggests that repulsion and ferromagnetic correlations may temporarily dominate the evolution of the many-body system also in the balanced case, for which a ferromagnetic instability is maximally favoured25. Regardless of whether the repulsive Fermi gas exhibits ferromagnetism at all, it is debated how its magnetic and transport properties are affected by the large coupling to lower-lying states.

In this work, we investigate the spin response and the stability of a balanced spin ↑−↓ mixture prepared in an artificial magnetic domain-wall structure (see Fig. 1b). Such a fully ferromagnetic initial configuration features a vanishingly small ↑−↓ density overlap in contrast to a paramagnetic state11,12. This greatly suppresses the effect of pairing processes, ensuring that the overall relaxation rate remains slow on the Fermi timescale, thereby maintaining the system on the upper branch for a comparatively long time. We probe the ferromagnetic properties of the repulsive

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Spin response of a repulsive Fermi gas

In a first experiment the spin dynamics is triggered by abruptly switching off the barrier in a 1 μs timescale. Owing to the small initial separation of about 5 μm, the two spin clouds approach each other with small relative momentum \( \hbar k \ll \hbar k_0 = \sqrt{2mE_F} \). We follow the clouds dynamics by resonant in situ absorption imaging, monitoring the evolution of the two spin domains (see Methods and Supplementary Information). On top of an overall slow drift, the relative distance between their centres of mass \( d(t) = z_r(t) - z_a(t) \) presents a small-amplitude out-of-phase oscillation, signalling the excitation of the spin-dipole mode (see Fig. 2a–c). The measurement of the spin-dipole frequency \( \omega_{SD} \), next to the one of spin fluctuations \( \omega_{S} \), is a powerful probe for disclosing the magnetic properties of harmonically trapped gases, connecting the local behaviour of the spin susceptibility \( \chi \) to a directly accessible quantity. Following a sum-rule approach \( \omega_{SD} \), the spin-dipole frequency \( \omega_{SD} \) is found to be:

\[
\omega_{SD} = \frac{N_1 + N_2}{4\pi m_i \int \, \mathrm{d}r^2 \, \chi(n(r))}.
\]

where \( \chi \) depends on the local density \( n(r) \) (see Methods). Whereas for a non-interacting gas \( \omega_{SD} = \omega_0 \), an increase of \( \chi \) in the repulsive Fermi liquid phase leads to \( \omega_{SD} < \omega_0 \)—that is, to a softening of the spin-dipole mode. Although \( \chi \) is locally divergent if a ferromagnetic instablity is reached at the trap centre, \( \omega_{SD} \) can only reach a non-zero minimum \( \omega_0 \) owing to the inhomogeneous density profile of the trapped gas, whose outer low-density paramagnetic region contributes with a small spin susceptibility. The measurement of this collective oscillation is challenging when starting from a paramagnetic configuration, due to strong damping \( \omega_{SD} \) and inelastic processes \( \omega_{SD} \). Here, instead, where the two spin domains just partially overlap over the timescale of the measurement, we are able to trace a few oscillation periods of the spin-dipole mode, from which we extract \( \omega_{SD} \) through a fit with a damped sinusoidal function (see Supplementary Information).

By tuning the magnetic field value, we perform such measurements at various repulsive interaction strengths—the results of which are displayed in Fig. 2d for two distinct temperatures. The interaction strength is described by the dimensionless parameter \( \kappa_{SD} \), where \( \kappa_{SD} \) is the average Fermi wave number (energy) weighted over the initial density distribution close to the interface between the two domains (see Methods). Focusing on the colder samples at \( T/T_F = 0.12(2) \) (blue circles in Fig. 2d), an increase of the interspecies repulsion lead to a progressive reduction of \( \omega_{SD} \), from \( \omega_{SD} \) to \( \omega_{SD} \) in the weakly interacting regime (see Fig. 2a) down to \( \omega_{SD} \) at about \( \kappa_{SD} \) (Fig. 2b). We find the decrease of \( \omega_{SD} \) to be accompanied by a strong increase of the damping of the oscillations \( \omega_{SD} \). By further increasing the interspecies repulsion, an abrupt change occurs in the spin dynamics: for \( \kappa_{SD} \), the spin-dipole frequency jumps sharply above the bare trap frequency, \( \omega_{SD} \) (see Fig. 2c), while the damping of the oscillations is strongly reduced. Once this narrow interaction region is crossed, a further increase of \( \kappa_{SD} \) does not produce any significant change.
neither in the damping rate nor in $\nu_{SD}$. Higher-temperature data exhibit a qualitatively similar trend, with the abrupt change in $\nu_{SD}$ occurring at a higher $\kappa_F a$ value. The observed trend of $\nu_{SD}$ up to $\kappa_F a \gtrsim 1$ agrees with the mode-softerning predicted by equation (1), reflecting a substantial increase in spin susceptibility. This is further supported by the good agreement of our high-temperature data with the spin-dipole frequency trend calculated in linear response\textsuperscript{25} (see green lines in Fig. 2d), inserting into equation (1) the susceptibility $\chi(\kappa_F a)$ from QMC calculations for a $T = 0$ homogeneous repulsive Fermi gas\textsuperscript{39} (see Methods). Furthermore, the value of $\nu_{SD}$ for $\kappa_F a > 1$, compatible with previous measurements at unitarity\textsuperscript{26}, compares well with the one expected for two immiscible clouds of unpaired fermions bouncing off each other\textsuperscript{37}, as if one spin component acted like an impenetrable potential barrier for the other. The increase of spin susceptibility detected up to a critical repulsion strength and the discontinuity of the spin response hint at a fermagnetic instability located at $\kappa_F a \approx 1$ for $T/T_c \gtrsim 0.12$.

The measured behaviour of $\nu_{SD}$ could not be explained if pairing processes dominated the system dynamics. On the lower branch, owing to effective attraction, the spin susceptibility decreases monotonically while crossing the Feshbach resonance from $a < 0$ to $a > 0$, vanishing completely for a Bose–Einstein condensate (BEC) of pairs. This trend equally occurs for the attractive Fermi liquid\textsuperscript{17}, the superfluid and the pseudo-gap state\textsuperscript{33,38}. Therefore, equation (1) implies a corresponding monotonic increase of $\nu_{SD}$ moving towards the BEC limit. We experimentally demonstrate this behaviour by intentionally initializing the system in the lower branch (see Supplementary Information), observing an increase of $\nu_{SD}$ even above $2v_1$ for $\kappa_F a > 0$ (see Fig. 2e). The measured spin response for the attractive gas is consistent with predictions from equation (1), obtained by inserting the spin susceptibility $\chi$ calculated for an attractive Fermi gas above the critical temperature for superfluidity\textsuperscript{38}, in agreement with previous measurements\textsuperscript{39}. In particular, it qualitatively differs from the spin response at $\kappa_F a > 0$ shown in Fig. 2d, leading us to conclude that the latter arises from paired fermions in the interface region. On the other hand, to confirm that during the spin dynamics shown in Fig. 2a–c the upper branch is indeed predominantly occupied, we estimate the molecular fraction under the same experimental conditions by an independent measurement (see Supplementary Fig. 6). We detect a molecular fraction not exceeding 15% after the first 50 ms of evolution for any $\kappa_F a$ value herein investigated, and below 5% for $\kappa_F a \gg 1$. Additionally, our findings seem incompatible with a purely collisional picture\textsuperscript{39} (see Supplementary Information), also considering the markedly distinct behaviour of $\nu_{SD}$ on the attractive branch shown in Fig. 2e.

**Observation of spin-domain immiscibility**

If the initially prepared fully fermagnetic state was indefinitely stable above a critical $\kappa_F a$, the two spin domains would remain immiscible—that is, spin diffusion would be impeded\textsuperscript{38}. To investigate this aspect, we study spin diffusion, exploring various interaction and temperature regimes. We initialize the dynamics by adiabatically lowering the barrier height through a 30 ms linear ramp from $V_0 \sim 10E_F$ down to $2E_F$, letting the two clouds
slowly approach each other. Their relative distance is reduced from about 5 \text{	extmu}m down to 1 \text{	extmu}m, yet each spin domain remains confined within its own reservoir. We then remove the barrier in 5 ms and we monitor the subsequent evolution of the relative population of the $i=\uparrow, \downarrow$ component in the left and right reservoirs, $M_i = (N_{\uparrow,i} - N_{\downarrow,i})/(N_{\uparrow,i} + N_{\downarrow,i})$, from which we obtain the magnetization $\Delta M = \langle M_i \rangle / 2$. Since the distance between the two nearby cloud edges is approximately equal to the local interparticle spacing at the interface between the two spin domains, this procedure does not excite any detectable spin-dipole oscillation.

Figure 3a shows the short-time evolution $\Delta M(t)$ for different interaction strengths: above a critical value of repulsion, after an initial slight decrease of $\Delta M$ from 1 to about 0.92, we indeed observe a time window during which spin diffusion is completely arrested. We attribute the initial drop in magnetization to spin transport within the low-density outer shells of the two spin clouds. The duration of the magnetization ‘plateau’ is however finite, since the stability of our ferromagnetic state is limited by the intrinsic tendency of the system to relax from the excited upper branch onto lower-lying energy states\(^{12,13,15}\) (see Fig. 1a). A thorough characterization of this interesting feature is summarized in Fig. 3b, where we plot the measured plateau duration $\tau_p$ of constant $\Delta M$ as a function of $1/(\kappa_F a)$, for various temperatures. The value of $\tau_p$ is determined through a piecewise linear fit to the data, yielding zero when no noticeable halt of spin dynamics is detected. A non-zero $\tau_p$ is detected only above a critical $\kappa_F a$ value and below a certain $T/T_F$. Notably, finite plateaux appear above an interaction strength nearly coincident with the one at which the spin-dipole mode frequency in Fig. 2d reaches its minimum and exhibits an abrupt change (see Fig. 3c). Furthermore, by increasing $\kappa_F a$ (increasing $T/T_F$), $\tau_p$ increases (decreases), reaching its maximum at the unitary point $1/(\kappa_F a) = 0$. On the other hand, no dynamical arrest is observed for $T/T_F \geq 0.7$. In addition, at low temperatures the trends for $\tau_p$ and $\nu_{SD}$ (see Figs 3c and 2e) suggest that we access the upper branch even within a narrow $1/(\kappa_F a) < 0$ region beyond unitarity, in accord with recent predictions\(^{15}\).

We find the behaviour of the plateau duration for $1/(\kappa_F a) > 0$ to be captured (see curves in Fig. 3b) by a phenomenological model based only on the knowledge of the lifetime and energy spectrum of the upper and lower branches of the many-body system\(^{24}\), calculated in the extremely polarized limit of one single $\uparrow (\downarrow)$ impurity embedded in a $\downarrow (\uparrow)$ Fermi gas\(^{12,24}\) (see Methods). Based on such a description, the ferromagnetic state is destroyed by inelastic processes occurring at the interface between the two...
macroscopic spin domains: fermions of one kind, overcoming the surface tension associated with a domain wall, can deposit an overall excess energy through decay from the upper to the lower branch. Only after some time, once a sufficient energy has been released into the system, is the domain wall melted and spin diffusion established.

Upon identifying for each temperature the lowest \( k F a \) value at which a non-zero \( \tau_F \) of steady magnetization is observed, we delimited a region in the interaction–temperature plane where the ferromagnetic domains remain temporarily immiscible, as displayed in Fig. 3d. The critical interaction strength for the onset of a non-zero \( \tau_F \) displays a nonlinear dependence upon temperature, and by fitting the \( T/T_F < 0.3 \) data points with \( T/T_F \propto ( (k_F a)/(T) - (k_F a)/(0) )^\alpha \), we obtain \( \alpha = 0.52(5) \) and \( (k_F a)/(0) = 0.80(9) \). The fitted exponent matches within its uncertainty the value \( \alpha = 1/2 \) expected from the low-temperature behaviour of a Fermi liquid exhibiting a magnetic instability (see Supplementary Information). The extracted zero-temperature value \( (k_F a)/(0) \) is interestingly found in good agreement with the critical value obtained from repulsive QMC calculations\(^ {20,21} \) and is significantly lower than Stoner’s mean-field criterion for an unpolarized gas\(^ {6,12,16-18,20} \), \( k_F a = \pi/2 \). Notwithstanding the metastable nature of the ferromagnetic state and the dynamical character of our study, our findings agree with theoretical expectations for a repulsive Fermi gas at equilibrium undergoing a ferromagnetic instability in the absence of pairing. Moreover, the close correspondence between the trends of \( \Upsilon_{2D} \) and \( \tau_F \) (see Fig. 3c) further suggests that the critical interaction strength for \( \tau_F > 0 \) corresponds to that required for the fully ferromagnetic state to be favoured.

Long-time diffusive dynamics and spin drag coefficient

Once spin diffusion is established\(^ {26-28} \), the analysis of the long-time evolution \( \Delta M(t) \) (or equivalently \( d(t) \)) within a simple kinetic model (see Methods) allows us to determine also the spin drag coefficient \( \Gamma_s \) as a function of temperature and interaction. The results are displayed in Fig. 4. These are compared with theoretical predictions for \( \Gamma_s \), calculated for a single impurity diffusing in a homogeneous ideal Fermi gas within kinetic theory, accounting for scattering in all available states within the \( T \)-matrix approximation for the scattering cross-section (see Supplementary Information). The model is able to quantitatively reproduce the measured maximum of \( \Gamma_s \) for \( T/T_F \geq 0.3 \), which is the expected range of validity of the \( T \)-matrix approximation, as well as the position of the maximum of \( \Gamma_s \) at all temperatures (see Fig. 4). At low temperatures the data sets exhibit a small but appreciable asymmetry around the unitary point towards \( k_F a > 0 \). Such a feature, which disappears progressively as temperature is increased, highlights the significant effect of collisions within the medium of surrounding particles on the dynamical properties of the diffusing quasi-particles (see Supplementary Information). A similar asymmetry in transport coefficients has already been reported for the shear viscosity\(^ {40} \) and transverse spin diffusion\(^ {41} \), but not in previous measurements of longitudinal spin diffusion\(^ {26} \).

Our studies of the time evolution of an engineered magnetic domain wall provide an important link between the dynamic response and the static properties of the repulsive Fermi gas, thereby pointing to a Stoner-like ferromagnetic instability. The techniques demonstrated for realizing and probing a spin-domain interface could be extended to different systems, opening new routes towards the investigation of dynamics in strongly correlated quantum mixtures, also in reduced dimensionality\(^ {42} \) or in the presence of weak optical lattices\(^ {43} \) and controlled disorder\(^ {26} \).

Note added in proof: After submission of the manuscript, we became aware of related theoretical work\(^ {44} \) by He et al., reporting finite-temperature predictions qualitatively consistent with our findings.

Methods

Methods, including statements of data availability and any associated accession codes and references, are available in the online version of this paper.

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Author contributions

G.V., F.S., A.A., M.I., M.Z. and G.R. carried out the experimental work. A.R. and G.V. , F.S., A.A., A.B., M.I., M.Z. and G.R. carried out the experimental work. A.R. and T.E. carry out the theoretical work. All authors contributed extensively to the discussion and interpretation of the data and results, and to the writing of the manuscript.

Additional information

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Competing financial interests

The authors declare no competing financial interests.
**Methods**

**Experimental protocols.** Our procedure to create weakly interacting two-component Fermi mixtures of Li atoms has been already described elsewhere (see Supplementary Information). The gas degeneracy parameter $T/T_F$ is adjusted by exploring the tunability of the collisional properties of $^6\text{Li}$ mixtures during evaporation. We typically end up with $N_L \approx 5 \times 10^4$ atoms, confined in a cigar-shaped harmonic potential characterized by an axial (radial) trap frequency of $\nu_1 = 21.0(1)$ Hz ($\nu_2 = 265.5(5)$ Hz). To spatially separate the two spin components, at a magnetic field of about 1 G, where the $\uparrow$ and $\downarrow$ states possess equal but opposite magnetic moments, we turn on a magnetic quadrupole gradient of about 1 G cm$^{-1}$ along the weak trap axis, which pushes the two spin clouds towards opposite directions. Once the overlap between the two components is zeroed, a repulsive optical potential barrier centred at $z = 0$, and characterized by a short (long) $1/e$ waist of $w_0 = 2.0(2)$ µm ($w_0 = 840(30)$ µm) is shone to confine the two clouds into two disconnected reservoirs. These are characterized by an axial oscillation frequency $\nu_z = 1.785(5)$, and no appreciable particle tunnelling is detected during more than 2 s with a barrier height of about 10$E_r$.

To excite the spin-dipole mode at a fixed Feshbach field, we abruptly switch off the barrier potential within less than 1 µs. The two spin clouds, initially separated by a distance of about 5 µm, start moving one towards the other at a small relative velocity. From here on, we monitor the dynamics of the relative distance between the centres of mass of the two components. For each value of evolution time, in two independent and successive experimental runs, we acquire two in situ absorption images with two high-intensity optical pulses, each of which is resonant only with one spin state. For each point of interaction, temperature, and evolution time, we perform a reduced overlap of 25% around the trap centre, in closer analogy to the experimental condition. In this case, the integral in equation (3) over the outer spin-polarized regions thus contributes only with the spin susceptibility $\chi_s$ of an ideal Fermi gas, yielding a reduction of the spin–dipole frequency from the bare trap frequency. Therefore, we expect the measured frequencies to be higher than the results of ref. 25, derived at full overlap. Consequently, the solid and dashed lines in Fig. 2 delimit a confidence region in which most experimental data are found. Most importantly, the critical interaction strength at which the abrupt change in $\sigma_{N_{\text{eff}}}$ occurs does not depend on the initial overlap configuration. Moreover, the spin diffusion dynamics happens on a longer timescale ($\gtrsim 200$ ms), as displayed in the Supplementary Information, compared to the spin–dipole period ($\sim 50–100$ ms). Hence, while we cannot assume that the system oscillates near an equilibrium configuration as in linear-response theory, the (slow) timescale for diffusion is sufficiently separated from the (faster) timescale for the spin oscillations.

**Polaron model for the domain-wall melting.** The proposed modelling of the plateau data shown in Fig. 3 proceeds as follows. In the case of purely repulsive interaction, the ferromagnetic state, if energetically allowed, would be indefinitely stable and the miscibility of the two components would be prevented by the existence of a domain wall. In particular, a fermion at the interface would need to expend a finite amount of energy $\sigma > 0$ to access the other spin domain forming a repulsive polaron at energy $E_r$. In our metastable system, however, if a repulsive polaron is created, it can subsequently decay onto the lower branch with a rate $\Gamma$, releasing an energy equal to the mismatch between the two branches, $E_r - E_\sigma$. Hence, this two-step process will cause a net increase of energy $\Delta E = E_r - E_\sigma - \sigma$ at a rate $\Gamma$. Importantly, the behaviour of $\Gamma$, $E_r$, and $E_\sigma$ as a function of the interaction strength can be derived from recent non-perturbative theory approaches$\textsuperscript{12,13}$.

We assume that at the beginning of the dynamics, the energy associated to the domain wall is given by $\sigma N_{\text{eff}}$, $N_{\text{eff}}$ being the total number of fermions within a slice around $z = 0$ of total thickness equal to one interparticle spacing. The duration of the plateau $\tau_p$ is then set by the condition:

$$\sigma N_{\text{eff}} = (E_r - E_{\sigma}) - \sigma \Gamma \tau_p$$

where $\sigma = \sigma_{N_{\text{eff}}}$, $E_\sigma$ is the energy of a repulsive polaron, while $E_r$ is the energy of one free fermion at the interface, left as a phenomenological parameter, and is independently adjusted for each $T/T_F$ herein investigated.

**Diffusion model for extracting the spin drag coefficient.** The equation for the dynamics of the relative centre of mass $z = z_\uparrow - z_\downarrow$ can be easily obtained from the Boltzmann equation and is written as (see Supplementary Information)

$$\frac{d}{dt} \langle z \rangle = \Gamma \frac{d}{dz} \langle z \rangle + \sigma_{\text{SD}} d = 0$$

where $\sigma_{\text{SD}}$ is the longitudinal trap frequency, and $\Gamma$ the spin drag coefficient due to collisions$\textsuperscript{26-27}$. We obtain the experimental spin drag coefficient by fitting the solution of equation (5) to the data, considering as initial condition $\langle z \rangle (0) = \langle z \rangle_0$ and $d(0) = 0$.

In Fig. 4 we compare the experimental results with a theoretical prediction based on a $T$-matrix approximation for the scattering cross-section corrected by the available scattering states to have a well-defined scattering amplitude in the ideal integral (see Supplementary Information). The agreement is especially good down to temperatures as low as $T = 0.3T_F$. At lower temperatures, both the shape and the magnitude of the spin drag coefficient as a function of the interaction compare more poorly. This is expected since at very low temperature the $T$-matrix approximation is not quantitatively correct; moreover, the gas may suffer some heating during the dynamics due to decay processes, making its temperature higher than that measured at the start of the dynamics, which is used for the comparison with the theory model.

**Data availability.** The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.