Anomalous dynamics of intruders in a crowded environment of mobile obstacles

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Many natural and industrial processes rely on constrained transport, such as proteins moving through cells, particles confined in nanocomposite materials or gels, individuals in highly dense collectives and vehicular traffic conditions. These are examples of motion through crowded environments, in which the host matrix may retain some glass-like dynamics. Here we investigate constrained transport in a colloidal model system, in which dilute small spheres move in a slowly rearranging, glassy matrix of large spheres. Using confocal differential dynamic microscopy and simulations, here we discover a critical size asymmetry, at which anomalous collective transport of the small particles appears, manifested as a logarithmic decay of the density autocorrelation functions. We demonstrate that the matrix mobility is central for the observed anomalous behaviour. These results, crucially depending on size-induced dynamic asymmetry, are of relevance for a wide range of phenomena ranging from glassy systems to cell biology.
n the presence of a confining medium, the transport of objects deviates from normal diffusion. Anomalous behaviour, usually manifested by the presence of sub-diffusivity, emerges as a common feature of the dynamics. In the Lorentz gas, the prototype model for anomalous transport, point-like intruders move in voids between immobile, randomly-distributed particles. Their motion becomes sub-diffusive once the voids are barely interconnected. When a critical density of immobile particles is reached, they percolate and the intruder becomes localized. Softness of the immobile particles or interactions among the intruders are known to modify this picture.

So far the slow movement of the host matrix has been largely ignored, despite representing realistic situations of biological and industrial interest. To address confined transport in slowly moving matrices, here we investigate a binary colloidal mixture of small and large hard spheres, of diameters \( \sigma_s \) and \( \sigma_l \), which represent intruders and host matrix, respectively. Changing the size ratio \( \delta = \sigma_s/\sigma_l \) we also modify the dynamic asymmetry of the system. We focus on volume fractions of large particles \( \phi_l > 0.5 \) approaching the glass transition, occurring at \( \phi_l^g \approx 0.58 \). In contrast the volume fraction of the intruders \( \phi_s \) is very small with \( x_s = \phi_s/\phi_l = 0.01 \).

Such a system combines the confinement of a dilute fluid of particles with large size-asymmetry are scarce. This might be due to limitations in the spatial and temporal resolution of confocal microscopy which make it difficult to track particles that are significantly smaller than another species of Brownian, that is, at most micron-sized, particles. To overcome these limitations, we keep the selectivity of fluorescent labelling (Fig. 1b), which allows us to separately determine the small and large particles. However, instead of tracking we employ the recent Differential Dynamic Microscopy (DDM) technique. This is based on the time correlation in Fourier space of the difference between images separated by a time delay \( \Delta t \) (Fig. 1c) and provides a measure of the characteristic time of the particle motions on the length scale \( q^{-1} \) within the time delay \( \Delta t \). The decay time is therefore related to the characteristic time of the particle motions on the length scale \( q^{-1} \). Approaches similar to DDM, like fluorescence correlation spectroscopy, do not provide information on the probed length scale. This information is crucial to investigate the effect on the dynamics of the size of the voids in which the small particles move. The function \( f(q, \Delta t) \) can also be obtained by dynamic light scattering, which, however, does not allow us to distinguish the two species by fluorescent labeling. We also study the same system by mode coupling theory (MCT) of the glass transition and, both in the case of mobile and immobile matrix particles, by numerical simulations, complementing the experimental results and providing insights on the underlying microscopic mechanisms. We observe anomalous dynamics of the small spheres at a critical size ratio \( \delta_c \) and we show that this dynamical behavior is intimately connected to the slow dynamics of the matrix of large particles.

Results

Small particle dynamics. Figure 2a–d shows the measured collective intermediate scattering functions \( f(q, \Delta t) \) of the small particles for size ratios \( \delta = 0.18 \) (Fig. 2a,c) and \( \delta = 0.28 \) (Fig. 2b,d) for different \( \phi \) and \( q \). For \( \delta = 0.18 \) and all \( \phi \) and \( q, f(q, \Delta t) \) versus \( \Delta t \) shows an initial decay, followed by a \( \phi \)-dependent intermediate plateau, and eventually a decay to zero at longer times (Fig. 2a). The initial decay can be associated with the Brownian motion of small particles within the voids of the large particles.
matrix. It becomes increasingly slower for increasing $\phi$ (Fig. 2a) and decreasing $q$, which means increasing length scale (Fig. 2c).

The intermediate plateau indicates the dynamical arrest of the collective dynamics, that is, of density fluctuations, and hence the absence of diffusion on the length scale determined by $q^{-1}$. The height of the plateau increases progressively with increasing $\phi$, similarly to the scenario, in which a percolation-type transition is approached from the collective $f(q, \Delta t)$ and self $f^{self}(q, \Delta t)$ correlation functions (Fig. 2i) for $\delta = 0.3$ and $\phi \approx 0.6$). The mean squared displacements (MSD) of the large particles are very slow and at intermediate times are indicating localisation and motion within nearest neighbour cages of approximate size $0.1 l_0$ (Supplementary Fig. 1 and Supplementary Note 1).

These results suggest the existence of a critical size ratio $\delta_c \approx 0.35$ at which pronounced anomalous dynamics mark the transition from a diffusive to a glassy regime of the small particles moving in the large particles matrix. The $\delta_c$ and $\phi$ values where this transition is observed are slightly smaller in the experiments than in the simulations. This is attributed to the fact that in the experiments small particles are polydisperse, while in the simulations they are monodisperse. Polydispersity is expected to affect the transition since the average size particles might still be able to diffuse through the void spaces in the matrix, whereas the largest particles of the size distribution might no longer be able to diffuse through them. The crossover observed at $\delta_c$ is analogous to the transition from a diffusive to a localized state in models with fixed obstacles. However, the excluded volume of the intruder generates a coupling with the host matrix and, due to the mobility of the matrix, also between intruders in different voids, mutuating localization into a glass transition due to the (slow) mobility of the matrix particles. Although this is apparently similar to intruders in a fixed matrix\(^{28-7,7}$, the logarithmic decay of $f(q, \Delta t)$ stands out as a novel feature.

On the basis of MCT, the appearance of logarithmic decays in $f(q, \Delta t)\^{30-32}$ is usually attributed to competing collective arrest mechanisms, like caging and bonding, and to higher-order glass transition singularities.\(^{33-35}$ We solved MCT equations for a binary mixture of hard spheres and $x_e = 0.01$. The resulting correlators $f(q, \Delta t)$ for a range of packing fractions around the MCT glass transition, $\phi_c \approx 0.516$ and $\delta = 0.2$ and $\delta = 0.35$, are shown in Fig. 3. No clear sign of logarithmic decay of $f(q, \Delta t)$ is found for these states in MCT: while an approximate logarithmic dependence does not take over, when probing a length scale of about $2l_0$ (Fig. 2b), which is comparable with the size of the matrix particles.
Visualisations of typical small particle locations in 2D show the distribution of the explored space for different values of q and increasing time. At small δ this is due to the fact that particles can easily move through channels connecting voids, and thus the explored space quickly associates into a percolating cluster. On the other hand, for large δ the creation of channels that allow the small particles to move between neighbouring void spaces is rare, and thus percolation of the explored space does not occur at t_{c, sim} and only voids corresponding to the size of monomers, dimers and fewmers are observed. This analysis reveals very different timescales at which the explored space percolates at different δ. These timescales depend, besides δ, on the timescale t_2 of the evolution of the void space, associated with the thermal motion of the matrix particles: yet this analysis is not offering substantial evidence that this mobility of the matrix is causing the logarithmic decays of the correlators observed at δ_c.

Comparison between mobile and immobile matrix. To go one step further and link the residual mobility of the matrix particles with the anomalous logarithmic decays, we perform additional simulations (for δ = 0.62) for immobile matrix particles and compare the dynamics of the intruders with the case of a mobile matrix. When the large particles are immobile (Fig. 5a), the MSD shows a sub-diffusive regime (MSD ~ t^2) followed by diffusion at long times (upward curvature) or localization (downward curvature), depending on δ. The crossover between these two long time behaviors takes place at a critical size ratio δ_{c, imm} ~ 0.275 where the MSD remains subdiffusive also at long times. The value of δ_{c} is smaller for the simulation with immobile large particles. This finding is consistent with the opening of channels as a consequence of the thermal motion of the matrix particles. In the case of mobile matrix particles localisation is never observed (Fig. 5b): even for large δ, the residual motion of the matrix allows the small particles to move and hence their MSD increases at long times. Furthermore, the subdiffusive regime observed in the case of an immobile matrix is only observed for δ < δ_{sim} and thus in a smaller range than for mobile particles. This is consistent with the opening of channels as a consequence of the thermal motion of the matrix particles, which allows larger particles to move between voids. We also find that f_{sim}(q, Δt) calculated for the case of an immobile matrix displays a power-law dependence on time extending for several decades (Fig. 5c), as also observed in the Lorentz gas model55, while the collective f(q, Δt) displays neither a power-law nor a logarithmic dependence (Supplementary Fig. 2 and Supplementary Note 2). In the case of

**Figure 3 | Dynamics of the intruders as predicted by MCT.** Intermediate scattering functions f(q, Δt) (top, middle) and mean-squared displacements ⟨Δr^2/2τ^2⟩ (bottom) describing the dynamics of small spheres in binary mixtures with size ratios delta below (left) and around (right) the onset of anomalous dynamics, for different magnitudes of the scattering vector q and total volume fraction φ (as indicated). Arrows indicate increasing φ or increasing q accordingly.
a mobile matrix, however, power law behaviour is not observed but, close to $d_c$, a logarithmic dependence is found. Thus, thermal motion of the matrix particles gives rise to the logarithmic decay, a novel type of dynamics which does not occur in models with immobile obstacles.

**Discussion**

Our combined experimental, simulation and theoretical study shows that dynamics of intruders in a mobile crowded environment requires a description beyond that provided by models with a matrix of fixed obstacles. The novel application of the confocal DDM technique to concentrated binary colloidal mixtures allows us to investigate the collective dynamics of intruders in a mobile matrix, revealing extended anomalous dynamics for specific values of the size asymmetry and of the probed length scale. While the Lorentz model predicts a power-law behavior, which is typical for systems close to a percolation transition, in the case of a mobile matrix we observe a logarithmic decay of the collective and self density fluctuations over at least three decades in time, at length scales comparable to the size of the matrix particles. This logarithmic decay marks the transition between a diffusive behaviour of intruders in a glassy medium for small size ratios $d_{o,d} < d_c$, where transient localization is due to the excluded volume of the mobile matrix, and glassy dynamics of the intruders at large size ratios $d_{o,d} > d_c$, due to crowding. Our results thus show that both percolation and glassy dynamics have to be considered. By comparing mobile and immobile matrix environments, we demonstrate that the dynamics of the small particles is profoundly altered, in a qualitative way, by the continuous evolution of channels in the mobile matrix, due to the thermal motion of large particles. A mobile matrix corresponds to an environment in which small intruders move in many real systems and applications, like in

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**Figure 4** | Illustration of the space explored by small particles during their motions. (a-b) Overlay of small particle positions at different times (colour coded from blue, corresponding to $t_{exp}=0 \text{ s}$ to red, corresponding to $t_{exp}=297 \text{ s}$ with time steps of 33 s), obtained by particle tracking applied to 2D confocal microscopy images, for $\phi = 0.60$ and (a) $\delta = 0.18$, (b) $\delta = 0.28$. (c) Positions of 10 small particles (distinguished by different colours) for (left) $\delta = 0.2$, (middle) $\delta = 0.35$ and (right) $\delta = 0.5$, for a fixed total time of the trajectories $t_{sim}=100t_0$, comparable with the experiments (d). Distribution $n(s)$ (normalized by the number of small particles $N_s$) of the size $s$ of clusters as defined in Methods, providing a measure of the space explored by small particles, evaluated within a fixed time interval $t_{sim}=100t_0$. For $\delta = 0.35$ data follow a power-law dependence $n(s) \sim s^{-2.19}$, consistent with random percolation (dashed line), while for $\delta = 0.20$ all particles belong to the same cluster. (e) Average size $L_c$ of finite clusters as a function of time, for different $\delta$, as indicated. The maximum in each curve signals the onset of percolation.
corresponding to 107 × 107 μm², were acquired at a fast rate of 30 frames per second to follow the short-time dynamics and at a slow rate, between 0.07 and 0.33 frames per second, depending on sample, to follow the long-time dynamics. Image series were acquired using a Nikon A1R-MP confocal scanning unit mounted on a Nikon Ti-U inverted microscope, with a 60 × Nikon Plan Apo oil immersion objective (NA = 1.40). The pixel size at this magnification is 0.21 × 0.21 μm. The confocal images were acquired with the maximum pinhole size allowed by the microscope, corresponding to a pinhole diameter of 255 μm. Time series of 10⁶ images were acquired for 2–5 different volumes, depending on sample.

**DDM analysis.** Particle movements induce fluctuations of the fluorescence intensity in the images, i(x, y, t), with x, y the coordinates of a pixel in the image and t the time at which the image was recorded. To obtain additional information on the characteristic length scales of particle motion, i(x, y, t), can be Fourier transformed, yielding i(q, t), with q the wave vector in Fourier space, and then differences of the Fourier transformed intensity images can be correlated (Fig. 1c) to obtain the image structure function D(q, Δt):

$$D(q, Δt) = \langle [i(q, t + Δt) - i(q, t)]^2 \rangle,$$

where [·] represents an ensemble average. This analysis technique is named DDM[3]. The intermediate scattering function f(q, Δt) (Fig. 1d) can be extracted from the image structure function:

$$D(q, Δt) = A(q)[1 - f(q, Δt)] + B(q),$$

with A(q) = N[K(q)]² S(q), where N is the number of particles in the observed volume, K(q) is the Fourier transform of the Point-Spread Function of the microscope, S(q) is the static structure factor of the system, and B(q) accounts for the camera noise. The inverse of the wave vector q determines the length scale over which the particle dynamics are probed. Thus f(q, Δt) is obtained, similarly to dynamic light scattering (DLS)[44] but for the present system the advantage of DDM over DLS is that fluctuations of the incoherent fluorescence signal can be correlated, a possibility which is excluded by the requirement of coherence of light in DLS. Furthermore, use of a confocal microscope drastically reduces the amount of background fluorescence of the measurements, significantly improving the determination of f(q, Δt). The effect of particles moving in and out of the observation plane on f(q, Δt) was found to be negligible for all samples, as determined by the q-dependence of the relaxation times of the initial decay of f(q, Δt), where no plateau at small q values was observed[25,45].

**Particle localization.** Coordinates of the small particles were extracted from time series of 2-dimensional images using standard particle localization routines based on the centroiding technique[46]. Only the particle positions at each time could be determined, not the full trajectories. Indeed the displacement of small particles during the time delay Δt between two successive frames is comparable or larger than their diameter, which implies that identifying particles after a Δt becomes too uncertain.

**Simulations.** We perform event-driven molecular dynamics simulations[47] in the cubic box ensemble in a cubic box with periodic boundary conditions for binary mixtures of hard spheres, of which the large components are 7% polydisperse by a discrete Gaussian distribution[48] and the small ones are monodisperse. For each studied θ we vary the total number of particles in the range of a few thousands. The number of small particles thus varies from 1980 for θ = 0.65 or 0.400. Brownian dynamics is enabled in a cubic box with periodic boundary conditions for binary mixtures of hard spheres, of which the large components are 7% polydisperse by a discrete Gaussian distribution[48] and the small ones are monodisperse. For each studied θ we vary the total number of particles in the range of a few thousands. The number of small particles thus varies from 1980 for θ = 0.65 or 0.400. Mass and length are measured in units of particle mass m, average large particle diameter σₗ, whereas time is in units of τₑ = m²σₗ² / kₐ T, where kₐ is the Boltzmann constant and T the temperature. For the simulations with immobile hard spheres, after equilibration of the mixture, we freeze the large particles only. To roughly estimate the critical size ratio which demarcates the transition between diffusive and localized states, we averaged results over ten different matrix realizations.

**Mode coupling theory.** The equations determining f(q, t) and (Δs(t)) within MCT were solved for a binary mixture of hard spheres within the Percus–Yevick approximation for the static structure; for details on the theory and the numerical procedure, see ref. 29. The f(q, Δt) were obtained using a wave-number grid of equidistant steps Δq = 0.4σ₀/q₀, with large-q cutoff q₀ = 400. Brownian dynamics is assumed with the short-time diffusion coefficients following the Stokes–Einstein relation; the diffusion coefficient of the large particles sets the unit of time Δt. In the calculations, the total packing fraction φ is varied, keeping xₗ = φ₁/φ₂ = 0.01 fixed.

**Calculation of the size distribution of the explored space.** To evaluate the distribution of space sampled by the small particles during time we employ the following procedure: First we generate a sequence of Nₛ configurations saved at equally spaced times tₛ (with i = 1… Nₛ) within a given time window τₛ. The time interval Δt between two successive configurations, i.e., Δtₛ = tₛ₊₁ − tₛ, is chosen in
such a way that \((\Delta r^2(\Delta t))/\tau^2 = 0.5\). Second, we overlap all \(N_i\) configurations and perform a cluster size analysis according to the following criteria: (i) the same particle at different times \(t_i\) belong to the same cluster; (ii) if two particles overlap, they belong to the same cluster; (iii) the size \(s\) of a defined cluster is the number of distinct particles belonging to the same cluster (running from one to the total number of small particles). To improve statistics we average the cluster size distribution over a set of at least 10 independent groups of \(N_i\) configurations. The average size of finite clusters is calculated as \(L = \sum n(s)/\sum s(n)\), excluding percolating clusters.

References

1. Klafter, J. & Sokolov, I. M. Anomalous diffusion spreads its wings. Nature Rev. Phys. 18, 29–32 (2005).
2. Höfling, F. & Franosch, T. Anomalous transport in the crowded world of biological cells. Rep. Prog. Phys. 76, 046602 (2013).
3. Lorentz, H. A. Le mouvement des électrons dans les métaux. Rev. Lett. 100, 71–711 (2010).
4. Srivastava, T. et al. Glass-like dynamics of collective cell migration. Proc. Natl. Acad. Sci. USA 108, 4714–4719 (2011).
5. Trimble, W. S. & Grinstein, S. Barriers to the free diffusion of proteins and lipids in the plasma membrane. J. Cell Bio. 208, 259–271 (2013).
6. Gravish, N., Gold, G., Zangwill, A., Goodisman, M. A. D. & Goldman, D. I. Glass-like dynamics in confined and congested ant traffic. Soft Matter 11, 6552–6561 (2015).
7. Cherdhirakorn, T. et al. Fluorescence correlation spectroscopy study of molecular probe diffusion in polymer melts. Macromolecules 42, 4858–4866 (2009).
8. Grabowski, C. A. & Mukhopadhyay, A. Size effect of nanoparticle diffusion in a polymer melt. Macromolecules 47, 7238–7242 (2014).
9. Narayanan, S., Lee, D. R., Hagman, A., Li, X. & Wang, J. Particle dynamics in polymer-metal nanocomposite thin films on nanometer-length scales. Phys. Rev. Lett. 98, 165506 (2007).
10. Kalathi, J. T., Yamamoto, U., Schweizer, K. S., Grest, G. S. & Sarkanen, K. S. Nanoparticle diffusion in polymer nanocomposites. Phys. Rev. Lett. 112, 108301 (2014).
11. Balsalobre, S., Gimel, J. C. & Nicolai, T. Tracer diffusion in colloidal gels. J. Phys. Chem. B 112, 743–748 (2008).
12. Salami, S., Rondeau-Mouro, C., van Duynhoven, J. & Mariette, F. Probe mobility in native phosophocaseinate suspensions and in a concentrated rennet gel: effects of probe flexibility and size. J. Agric. Food Chem. 51, 8570–8579 (2003).
13. Hebling, D. Traffic and related self-driven many-particle systems. Rev. Mod. Phys. 73, 1067–1141 (2001).
14. Cercino, R. & Trappe, V. Differential dynamic microscopy: probing wave vector dependent dynamics with a microscope. Phys. Rev. Lett. 100, 188102 (2008).
15. Lu, P. J. et al. Characterizing concentrated, multiply scattering, and actively driven fluorescent systems with confocal differential dynamic microscopy. Phys. Rev. Lett. 108, 218103 (2012).
16. Wilson, L. G. et al. Differential dynamic microscopy of bacterial motility. Phys. Rev. Lett. 106, 081801 (2011).
17. Gotze, W. & Hausmann, R. Further phase transition scenarios described by the self consistent current relaxation theory. Z. Phys. B: Condens. Matter 72, 403–412 (1988).
18. Rosse, J. & Kaneko, Y. Self-diffusion in supercooled binary liquids. Phys. Rev. Lett. 74, 4023–4026 (1995).
19. Voigtmann, T. Multiple glasses in asymmetric binary hard spheres. Europhys. Lett. 96, 36006 (2011).
20. Moreno, A. J. & Colmenero, J. Logarithmic relaxation in a kinetically constrained model. J. Chem. Phys. 125, 016101 (2006).
21. Moreno, A. J. & Colmenero, J. Relaxation scenarios in a mixture of large and small spheres: dependence on the size disparity. J. Chem. Phys. 125, 164507 (2006).
22. Mayer, N. et al. Multiple glass transitions in star polymer mixtures: Insights from theory and simulations. Macromolecules 42, 423–434 (2009).
23. Dawson, K. et al. Higher-order glass-transition singularities in colloidal systems with attractive interactions. Phys. Rev. E 63, 011401 (2000).
24. Sciotino, F., Tartaglia, P. & Zaccarelli, E. Evidence of a higher-order singularity in dense short-ranged attractive colloids. Phys. Rev. Lett. 91, 268301 (2003).
25. Gnan, N., Das, G., Sperl, M., Sciotino, F. & Zaccarelli, E. Multiple glass singularities and iodynamic in a core-softerned model for glass-forming systems. Phys. Rev. Lett. 113, 258302 (2014).
26. Stauffer, D. & Aharony, A. Introduction to Percolation Theory 2nd ed. (CRC Press, 1994).
27. Spanner, M., Schnyder, S. K., Höfling, F., Franosch, T. Dynamic arrest in model porous media-intermediate scattering functions. Soft Matter 9, 1604–1611 (2013).
28. Yethiraj, A. & van Blaaderen, A. A colloidal model system with an interaction tunable from hard sphere to soft and dipolar. Nature 421, 513–517 (2003).
29. Royall, C. P., Poon, W. C. K. & Weeks, E. R. In search of colloidal hard spheres. Soft Matter 9, 17–27 (2013).
30. Schiwill, W. & Sillescu, H. Brownian dynamics of polydisperse colloidal hard spheres: equilibrium structures and random close packings. J. Stat. Phys. 77, 1007–1025 (1994).
31. Desmond, K. W. & Weeks, E. R. Influence of particle size distribution on random close pack of spheres. Phys. Rev. E 90, 022204 (2014).
32. Poon, W. C. K., Weeks, E. R. & Royall, C. P. On measuring colloidal volume fractions. Soft Matter 8, 2130–2140 (2012).
33. Mason, T. G. Estimating the viscoelastic moduli of complex fluids using the generalized stokes-einstein equation. Rheol. Acta 39, 371–378 (2000).
34. Berne, B. J. & Pecora, R. Dynamic Light Scattering: With Applications to Chemistry, Biology, and Physics (Dover Books on Physics) (Dover Publications, 2000).
35. Giaffezzi, F. & Cerbino, R. Digital fourier microscopy for soft matter dynamics. J. Opt. 16, 083001 (2014).
36. Crocker, J. C. & Grier, D. G. Methods of digital video microscopy for colloidal studies. J. Coll. Interf. Sci. 179, 298–310 (1996).
37. De Michele, C. Simulating hard rigid bodies. J. Comput. Phys. 229, 3276–3294 (2010).
38. Zaccarelli, E. et al. Crystallization of hard-sphere glasses. Phys. Rev. Lett. 103, 135704 (2009).

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Author contributions

T.S., S.U.E. and M.L. planned, performed, analysed and interpreted the experiments. E.Z., F.S. and M.L. planned, ran and interpreted the simulations. T.V. obtained MCT predictions. All authors contributed to the interpretation and comparison of the data as well as the writing of the manuscript.

Additional information

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