Tunable depletion force in active and crowded environments

Fane Feng, Ting Lei, and Nanrong Zhao*

Department of Physical Chemistry, College of Chemistry, Sichuan University, Chengdu 610065, China

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We adopt two-dimensional Langevin dynamics simulations to study the effective interactions between two passive colloids in a bath crowded with active particles. We mainly pay attention to the significant effects of active particle size, crowding-activity coupling, and chirality. First, a transition of depletion force from repulsion to attraction is revealed by varying particle size. Moreover, larger active crowders with sufficient activity can generate strong attractive force, which is in contrast to the cage effect in passive media. It is interesting that the attraction induced by large active crowders follows a linear scaling with the persistence length of active particles. Second, the effective force also experiences a transition from repulsion to attraction as volume fraction increases, as a consequence of the competition between the two contrastive factors of activity and crowding. As bath volume fraction is relatively small, activity generates a dominant repulsion force, while as the bath becomes concentrated, crowding-induced attraction becomes overwhelming. Lastly, in a chiral bath, we observe a very surprising oscillation phenomenon of active depletion force, showing an evident quasiperiodic variation with increasing chirality. Aggregation of active particles in the vicinity of the colloids is carefully examined, which serves as a reasonable picture for our observations. Our findings provide an inspiring strategy for the tunable active depletion force by crowding, activity, and chirality.

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I. INTRODUCTION

The significance of crowding in biology is gaining increasing appreciation because of the realization that biochemical processes generally occur in a dense medium containing a large number of macromolecules including proteins [1,2], ribosomes [3], membranes [4], etc. Interparticle effective force mediated in a crowding environment, usually called depletion force, is of paramount importance in advancing our understanding of how to steer the pivotal processes, such as molecular diffusion [5–9], protein-protein association [10], self-assembly of supramolecular structures [11], genome compaction [12], and so on.

A typical crowding system could possibly contain diverse active particles. An important example of active matter is constituted by natural and artificial objects capable of self-propulsion, including, for example, molecular motors [13], microtubules [14], active filaments [15], and artificial self-propelled swimmers [16,17]. Unlike passive particles, active entities can convert internal energy into direct motion and put various processes out of equilibrium [18–21]. Active matter systems often exhibit exotic behaviors not found in passive systems, including complex collective motions [22,23], active swarming [24,25], large-scale vortex formation [26], and motility-induced phase separation [27–31]. Recently, there is growing theoretical and experimental interest in exploiting what kind of interactions emerge between passive particles in the presence of an active medium [32]. The resulting force has been called active depletion, as this is the natural generalization of the depletion forces arising in passive baths [33]. Deep insight into active depletion force is relevant to a wide range of disciplines including nonequilibrium statistical mechanics, biology, colloidal science, and soft matter physics [34–36].

As two macromolecules or colloidal particles are suspended in a bath by the addition of numerous small, nonadsorbing components such as asymmetric binary mixtures, effective interactions between the large colloidal particles arise by means of depletion forces. Supposing the components are passive particles which could finally relax to an equilibrium state determined by the interaction potential and temperature, the effective interactions result in an attractive force. This attraction emerges when two colloids come in close enough proximity for their excluded volumes to overlap. The overlap of the excluded volume around the large colloids increases the volume available to the small background components. Hence, the total entropy increases, which favors the equilibration of the system. In recent decades, depletion interactions in passive systems have received a lot of attention. For instance, depletion-induced crystallization in colloidal rod-sphere mixtures has been studied by experiments [37]. Tunable depletion potentials driven by shape variation of surfactant micelles were measured [38]. A microscopic theory of polymer-mediated interactions between spherical particles was proposed [39]. Coarse-grained molecular dynamics and a hybrid Monte Carlo plus integral equation theory approach were adopted to evaluate the depletion interactions in soft matter systems [40–42]. Recently, Groen et al. used a Fluorescence Resonance Energy Transfer (FRET)-based probe to systematically study depletion in vitro in different crowded solutions of biopolymers [43].

When two colloids are held in an overwhelming number of small active particles, the behaviors of immersed colloids are driven to be far from equilibrium, and the effective
interactions among them are determined by an interplay between random fluctuations and swimming of the active agents \([44,45]\). In active systems, the excluded volume effect cannot be the sole cause for the effective interactions, and the associated entropy scenario is not enough to describe the underlying physics. The peculiar nonequilibrium features of the dynamics of the self-propelled particles introduce other mechanisms to the effective interactions. In recent years, considerable work has been devoted to the active matter mediated interactions, and a series of phenomena have been observed which are not attainable by matter at thermal equilibrium \([46–50]\).

Active depletion force could be attractive or repulsive depending, e.g., on the shape of the colloids, the activity mechanism, and the magnitude of activity subject to bath particles. It was found that the shapes and orientations of the intruders influence both the short-ranged (depletion) forces \([51]\) and long-ranged Casimir-like interactions \([52]\). Angellani \emph{et al.} studied the effective interactions between spherical colloids suspended in a bath of swimming cells following run-and-tumble dynamics \([53]\). Results indicate that the features of the interaction arise from the combination of nonequilibrium dynamics and excluded volume effects. Harder \emph{et al.} investigated how the range, strength, and sign of the active depletion are dependent on the shape of the colloids \([51]\). Casimir effects in active matter systems have gained a lot of attentions recently \([54,55]\). The forces induced by an active bath on two plates of a given length were measured, and layering effects and tunable long-range forces between plates were reported. The effective forces between two wedges immersed in an active bath was studied by Brownian dynamics simulations \([56]\). A phenomenon was revealed that transition from repulsion to attraction occurs by varying both apex angle and wedge-to-wedge distance. Additionally, using simulations and experiments, Liu \emph{et al.} directly measured forces in steady states, demonstrating that the active depletion forces on passive colloidal objects are greatly influenced by the elastic or kinematic constraints on the objects \([57]\).

In spite of the great efforts so far, there still remain challenging problems. Note that the previous works mainly focus on how details of bath activity and geometry of immersed colloids affect active depletion force. Less attention is paid to the crowding aspect of the active bath. In fact, effective interactions between two colloids in a crowded and active medium will suffer from a significant crowding-activity coupling effect. On the one hand, crowding strengthens the excluded volume effect and thus enhances attractive interactions. On the other hand, activity usually plays a role to provide repulsive effective interactions, arising from the accumulation of the active particles near the concave gap formed by the colloids. With increasing bath concentration, for example, more active particles participate to exert nonequilibrium interactions on the colloids. As a consequence, the accumulation behavior and the resultant repulsive depletion force will be seriously adjusted. It is evident that attraction induced by excluded volume effect and repulsion associated to activity effect are functions of crowding condition. In most situations, crowding and activity are two contrastive factors which determine the active depletion force in a complicated manner. To the best of our knowledge, however, a systematic understanding of such a crowding-activity coupling effect on the active depletion force is still lacking.

In addition, it is worth noting that bath particle size effect can be also crucial and relevant to both crowding and activity effects. As already mentioned, crowding plays a role to substantially influence the excluded volume effect, which undoubtedly depends on crowder size. Previous works for passive media, including Asakura and Oosawa's (AO) theory, have verified the attractive depletion force subject to the immersed colloids can be enlarged by increasing the ratio size between colloids and passive depletants \([33]\). Activity effect is associated with both active force and active particle size. Indeed, in active matter systems, the dynamics of active particles is characterized by the persistence length \(L\) which measures the distance of the particle moving along the direction of its original orientation: \(L \sim F_a \sigma^2_a/3\), with \(F_a\) being the active force and \(\sigma_a\) being the active particle size. It is evident that both \(F_a\) and \(\sigma_a\) play similar roles to feature the particle's self-propulsion ability. In the previous studies on effective interactions in an active bath, the active depleting agents were usually treated as spherical particles with fixed size, and most attention was paid to the influence of varying active force. In real active and crowded media, however, the active crowders could have different sizes. Investigating the associated size effect on active depletion force is definitely a necessary task.

Lastly, chirality can be another important factor to the relevant problem. In real active matter systems, the motion of particles may suffer from a dynamical chirality besides activity \([58–61]\). Unlike nonchiral particles, chiral ones are affected by both active force and an extra torque, resulting in a motion along circular trajectories in two dimensions and along helical trajectories in three dimensions. The occurrence of microorganisms swimming in circles has been observed in many situations, in particular, close to a substrate for bacteria \([62,63]\) and spermatozoa \([59,64]\). It has been found that the chiral feature of active particles can affect significantly the collective dynamics including transport \([65–68]\), separation \([69,70]\), and sorting \([71,72]\). Because of the more complex nonequilibrium dynamics, effective force induced by chiral particles should follow a different scenario from that induced by nonchiral ones. Unfortunately, chirality effect on active depletion force remains poorly understood.

Motivated by the above considerations, in the present work, we study the effective interactions between two passive colloids in a bath crowded with active particles, by using Langevin Brownian dynamics simulations. We extensively evaluate the dependence of active depletion force on various system parameters, including crowder size, bath volume fraction, and particle active force and angular velocity. The significant effects of active particle size, crowding-activity coupling, and have been carefully examined. Transitions of depletion force from repulsion to attraction induced by varying active particle size and volume fraction are identified. Moreover, we observe an interesting oscillation behavior of active depletion force with increasing chirality. Aggregation of active particles in the vicinity of probed colloids is also investigated, which serves as a reasonable understanding for the underlying mechanism of the active depletion interactions.

The remainder of this paper is organized as follows: In Sec. II, we describe our model and simulation method. In
Sec. III, we present our results and discussion, followed by conclusions in Sec. IV.

II. MODEL AND METHOD

We evaluate the effective interaction force between two colloids in an active bath based on a two-dimensional Langevin Brownian dynamics simulation. Figure 1 shows the sketch of our model. Here, the two colloids (blue) are assumed to be passive and fixed at a distance r. Bath is crowded by active particles (orange) subject to an active force \( F_a \). Besides, the dynamic chirality of the active particle will be also considered in our model analysis, with \( \omega \) being the rotating angular velocity. The diameters of colloids and active particles are prescribed to be \( \sigma_c \) and \( \sigma_a \), and the bath volume fraction is \( \phi \). Two vertical dashed lines mark two different regions around the passive particles, in which the active particles contribute differently to effective force. Regions I and II respectively refer to the concave area near inner surface and the convex area near outer surface of the colloids. Collisions occurring in region I generate effective repulsion, which pushes two colloids apart. Attraction is generated when active particles in region II strike the outer surface of the colloids, inducing the colloids toward each other. The total depletion force is the result of competition of the attractive and repulsive forces, which is determined by the distribution of particles in regions I and II. Evidently, the active bath properties, such as active force, volume fraction, particle sizes, and chirality, have a significant impact on particle distribution and thus tune effectively the depletion force.

We would like to point out that in the design of our study, the two large particles are assumed to move very slowly relative to the dynamics of the active particles. The accumulation of active particles in the two different regions, I and II, does not happen instantaneously and is instead something that builds up over time with the large particles held fixed. The resultant effective force is in large part determined by this type of dynamical accumulation. We measure the effective force from an ensemble of configurations over a long time after the system reaches a steady state. The present work is limited to systems such as massive (or large) objects suspended in light (or small) active particles. If the dynamics of colloids cannot be negligible, one faces a different system where the dynamical motions of both colloids and active particles have to be taken into account simultaneously. As a result, not only the accumulation behavior but also the generated effective forces will be different from the present study.

Interaction between any two active particles and that between active particle and colloid are modeled via the purely repulsive Weeks-Chandler-Andersen (WCA) potential, given by

\[
U = \begin{cases} \epsilon \left( \frac{\sigma_i^6}{r_{ij}^6} - \left( \frac{\sigma_i}{r_{ij}} \right)^{12} + \left( \frac{\sigma_i}{r_{ij}} \right)^6 + \frac{1}{4} \right), & r_{ij} \leq r_{\text{cut}} \\ 0, & r_{ij} > r_{\text{cut}} \end{cases}
\]

(1)

where \( \sigma_{ij} = (\sigma_i + \sigma_j)/2 \), with \( \sigma_{ij} \) being the diameter of the pairwise interacting particles. The energy is truncated at \( r_{\text{cut}} = 2^{1/6} \sigma_{ij} \), \( \epsilon \) and \( r_{ij} \) denote the interaction strength and the center-to-center distance between the two sites respectively.

The dynamics of each active particle is described by the following Langevin equation:

\[
m_a \frac{d^2 r_a}{dt^2} = -\gamma_a \frac{dr_a}{dt} - \nabla r_a U + \xi_a(n(\theta) + \sqrt{2\gamma_a^2 \Delta t} \Gamma_\theta(t)),
\]

(2)

where \( m_a \) is the mass of the active particle and \( \gamma_a \) is the friction coefficient subject to the active particle in pure solvent. \( \Delta t \) refers to the translation diffusion coefficients. \( n(\theta) = (\cos \theta, \sin \theta) \) denotes the unit vector along the propelling axis of the active particle, with \( \theta \) being the angular variable. For a nonchiral active particle, \( \theta \) evolves with time according to

\[
\frac{d\theta}{dt} = \sqrt{2D_1} \Gamma_\theta(t)
\]

(3)

with \( D_1 \) being the rotation diffusion coefficient. The Einstein-Stokes relation is satisfied, which indicates \( D_1 = 3D_2/\sigma_a^2 \). Evidently, unlike a passive particle, the dynamical motion of an active particle is determined by the coupled stochastic evolutions of both translation and rotation, given by Eqs. (2) and (3) respectively. The solvent-induced Gaussian white noises \( \Gamma_\theta(t) \) and \( \Gamma_\phi(t) \) applied to both translational and rotational motions are characterized by zero mean and unit matrix of autocorrelation function, i.e., \( \langle \Gamma_\phi(t) \rangle = 0 \), \( \langle \Gamma_\phi(t) \cdot \Gamma_\phi(t') \rangle = \delta(t - t') \), and \( \langle \Gamma_\theta(t) \rangle = 0 \), \( \langle \Gamma_\theta(t) \Gamma_\theta(t') \rangle = \delta(t - t') \).

For a chiral active particle, the evolution of \( \theta \) is determined by

\[
\frac{d\theta}{dt} = \omega + \sqrt{2D_1} \Gamma_\theta(t),
\]

(4)

where the additional angular velocity \( \omega \) is introduced to account for the influence of the deterministic dynamical rotating to the evolution of particle direction.

In our model system, mass and diameter units are denoted as \( m \) and \( \sigma \cdot k_B T \) is set to be energy unit. Then, time is scaled by \( \tau_0 = \sqrt{m\sigma^2/k_B T} \). Active force \( F_a \) and angular velocity \( \omega \) of active particles are scaled by \( k_B T/\sigma \) and \( 1/\tau_0 \) respectively. The mass of active particles relates with mass unit according to \( m_a = m(\sigma_a/\sigma)^2 \). The translation diffusion coefficient \( D_1 \) is given by \( D_1 = \frac{k_B T}{\gamma_a} \) with \( \gamma_a = \frac{\gamma}{\sigma_a^2} \). Here, \( \gamma \) is the friction coefficient subject to the particle with diameter unit \( \sigma \). In our simulation, we fixed \( \gamma = 10m\tau_0^{-1} \). Besides, the interaction strength is prescribed to be \( \epsilon = 40k_B T \).
The velocity Verlet method is used to integrate Newton’s equation of motion. A Langevin thermostat is employed to maintain temperature for an adequate sampling of the conformational space of the system. The simulation integration time step is set to be $10^{-4}t_0$. After initial equilibration of the system, simulation is then run for $\approx 2 \times 10^6$ time steps, and data are obtained every 10 steps. The entire simulation is repeated 20 times with different random choices of initial system conformations. Ensemble averages are obtained as a time average within each run, which is then averaged over different simulations to compute the quantities of interest.

The entire system is enclosed in a two dimensional $l \times l$ box with $l = 150\sigma$. The periodic boundary condition is adopted. In our simulation, the largest particle is less than $5\sigma$. The box width prescribed is large enough so that the finite-size effect has been sufficiently avoided.

III. RESULTS AND DISCUSSION

Now, we are able to resolve the effective interaction between two colloids in an active bath. We quantify the effective force $F_{\text{eff}}$ between the frozen colloids through directly accumulating the average force on the passive colloids exerted by the active particles in a small range of separation around $r$ in the steady state. The diameter of the colloids is fixed at $\sigma_c = 5.0\sigma$. The variable parameters include active force $F_a$ and diameter $\sigma_a$ of the active particle, the volume fraction $\phi$, as well as the chirality $\omega$ of the active particle. Effects of activity and crowding coupling on $F_{\text{eff}}$ will be explicitly investigated. Besides, the interpretation for the size effect can be conveniently involved. Introducing different crowder sizes, the nonbond interaction energy between crowders and passive colloids will be modulated, through adjusting the diameter of the pairwise interacting particles. In addition, chirality changes the motion path of active particles through the angle evolution equation, and thus will lead to different activity effects. In what follows, we will clarify in detail the active particle size dependence of $F_{\text{eff}}$, the bath active crowding coupling effect, and the crucial chirality effect of active bath in a systematic manner.

A. Nontrivial active crowder size effect

We focus on the crowder size effect on the effective interaction force. For such a purpose, we evaluate $F_{\text{eff}}$ under various active forces $F_a$ and particle sizes $\sigma_a$. The volume fraction of the bath is tentatively fixed at $\phi = 0.1$. $F_a$ ranges from 0 to 50 and $\sigma_a$ varies in between 1.0 to 4.0. For simplicity, we here deal with a nonchiral bath by setting $\omega = 0$ in Eq. (4). The chirality effect will be analyzed in detail in Sec. III C.

First, we investigate the activity effect at a fixed crowder size $\sigma_a = 1.0$. Figure 2 shows the depletion force $F_{\text{eff}}(r)$ normalized by active force $F_a$ as a function of the scaled distance $(r - \sigma_c)/\sigma_a$ under various active forces $F_a$. In passive bath, depletion force between two colloids is attractive as expected. When the self-propulsion of bath particles is introduced, the depletion force gradually turns to be repulsive and the strength of the repulsion dramatically increases with $F_a$. Such an attraction-to-repulsion transition induced by activity observed here is consistent with the previous work [51]. Moreover, the effective force under various activity exhibits oscillation with increasing distance $(r - \sigma_c)/\sigma_a$. In particular, for moderate active force $F_a = 30$, a more remarkable oscillation behavior appears, manifesting a stronger first peak followed by a weaker second peak. The location of the first peak of $F_{\text{eff}}(r)$ tends to a shorter range separation between two colloids as $F_a$ becomes larger, that is, the greater the activity is, the earlier the first peak emerges. At long-range separation, all depletion forces becomes negligible as $(r - \sigma_c)/\sigma_a \simeq 4$. Varying $F_a$ does not significantly affect the distance at which depletion force vanishes gradually.

We would like to address that the effective force $F_{\text{eff}}(r)$ obtained here terminates in a short-ranged distance. Note that recently Ni et al. revealed a long-range force induced by hard sphere active particles between two parallel hard walls [55]. The resulting force can be tuned from a long-range repulsion into a long-range attraction by changing the density of active particles and the height of the confinement. This phenomenon indicates a significant Casimir effect in active matter systems, which can be interpreted by the formation and destruction of dynamic crystalline bridge made of active particles. In the present work, we analyze active particle induced effective interactions between two disks. The geometry of the colloids is different from Casimir confinement. Unlike the two parallel hard walls, disks have curved surfaces, so active bath particles which come into contact with the surface of the disk cannot be strongly confined to move along this surface until they rotate away. Then active particles can only form dynamic clusters with limited size near the surface area of the colloids, while long-range dynamic crystal layering hardly appears. As a consequence, a short-ranged effective force similar to that in passive systems is generated. This is in accordance with the previous studies [47,51,57] which dealt with a similar system of disk colloids in an active bath. According to our observations, the presence of activity plays a role in modifying the magnitude and the sign of the effective force, while it has little influence on the length scale of the effective interactions.
active force is given to be $F_a = 30$. In addition, contact with increasing crowder size will become more prominent as active force is larger (see Fig. 4 below). In passive case, however, can be either attraction or repulsion, depending on both active force and crowder size. Two regimes of depletion force, i.e., attraction (bottom panel) and repulsion (upper panel), are depicted. Inset is the magnification for $F_a = 0$, 10, and 20. The typical regions of attraction and repulsion are denoted. Error bars correspond to one standard deviation.

Second, we examine the crowder size effect at a given active force $F_a = 30$. Figure 3 presents the variation of $F_{\text{eff}}(r)/F_a$ with respect to the scaled distance $(r - \sigma_c)/\sigma_a$ under various crowder sizes $\sigma_a$. As in Fig. 2, the depletion force exhibits remarkable oscillation behavior, exhibiting a repulsive feature except in contact (i.e., $r = \sigma_c$). The whole profile of $F_{\text{eff}}(r)/F_a$ declines (becomes less repulsive) with increasing $\sigma_a$. The first peak in the closest separation is the most distinguishable. In spite of different crowder size, the location of the peak is almost overlapped. We see the colloids will experience the strongest repulsive force as $0.5 < (r - \sigma_c)/\sigma_a < 1.0$. In such distance region, swimmers generate repulsive force from their accumulation in the concave region I around the colloids. The concave region I increases with crowder separation $r$, while the collision area in the convex region II remains constant, leading to the increment of effective force $F_{\text{eff}}$. The effective force reaches the maximum at $(r - \sigma_c)/\sigma_a \approx 1.0$. Further increasing the separation creates a gap that allows one swimmer to easily pass through without being trapped. $F_{\text{eff}}$ then sharply reduces. As $(r - \sigma_c)/\sigma_a$ approaches to 2.0, the gap between the colloids can be jammed by two swimmers with a certain probability. $F_{\text{eff}}$ increases again, manifesting the second and weaker peak. Note that as activity is large enough (e.g., $F_a = 50$ in Fig. 2), the first peak tends to locate at a closer separation, which indicates swimmers have stronger ability to intrude into the concave region of the colloids to generate repulsive force. Even though repulsive feature is dominant as colloids are separated, the depletion force in contact exhibits a transition from repulsion in the case of small $\sigma_a$ to attraction in the case of large $\sigma_a$. Such a repulsion-to-attraction transition in contact with increasing crowder size will become more prominent as active force is larger (see Fig. 4 below). In addition, notice that the range of the effective interaction is sensitive to crowder size. Smaller crowders extend the interaction to a longer distance.

Based on the above analyses, we go forward to address the activity effect associated with crowder size by evaluating the depletion force in contact, i.e., $F_{\text{eff}}(r = \sigma_c)$. Figure 4 displays $F_{\text{eff}}(r = \sigma_c)$ as a function of crowder size $\sigma_a$ under various active forces. Two regimes of depletion force, i.e., attraction (bottom panel) and repulsion (upper panel), are depicted. Inset is the magnification of profiles for $F_a = 0$, 10, and 20. It is noticeable that the effective force (either attraction or repulsion) increases with active force. The concept of effective temperature $T_a$ can be introduced to measure the strengthened collisions in the presence of activity. One might be tempted to think that the stationary states of active Brownian systems could resemble equilibrium states at a higher effective temperature, taking the form of $T_a = k_B T_0 \gamma_0 a^2$. Here, $\gamma_0 \sim \sigma_a$ is the friction coefficient subject to active particles. $T_0$ denotes the rotational characteristic time in proportional to $\sigma_a^2$. The velocity of active particle $v$ is given by $F_a/\gamma_0 a$. Thus, we have $T_a \sim F_a a^2 \gamma_0$. This is determined by $F_a$ and $\sigma_a$ simultaneously. $T_a$ measures in what extent bath activity takes an effect. The enhancement of effective temperature implies stronger collisions between colloids and active particles, leading to a larger effective force as observed.

In passive case [$F_a = 0$; open symbols], the depletion force is definitely attractive, and the strength of the force decreases with $\sigma_a$. This observation is in agreement with the previous coarse-grained molecular dynamics simulations [41] and AO model [33]. Introducing activity, the depletion force in contact, however, can be either attraction or repulsion, depending on both active force and crowder size. In the case of a small active force $F_a = 10$, the depletion force remains attractive in the whole range of $\sigma_a$, similar to that in the passive case, while the attraction strength is apparently enhanced by activity. Under such small activity, the active particles behave in a manner similar to that of the passive ones, in that particles mainly aggregate in the convex region of the colloids. While the presence of activity indicates a higher effective temperature of the bath, stronger collisions from the outside surface of the colloids are inevitable, resulting in larger attractive force.

Very interestingly, as $F_a$ further increases (see the profiles for $F_a \geq 20$), an unusual transition between attraction...
and repulsion is involved. The depletion force demonstrates a crossover from repulsion regime in small $\sigma_a$ to attraction regime in large $\sigma_a$. Such transition phenomenon becomes more remarkable as $F_a$ is larger. Moreover, the critical crowder size for transition locates at $\sigma_a \approx 2.5$, half the size of the colloid diameter. The repulsive to attractive transition as described above in the large activity regime is surely the consequence of the competition of particle accumulation in concave and convex regions around the colloids. As already pointed out by Harder et al. [51], unlike equilibrium systems for which one expects a particle to bounce off a wall upon collision, the collision of an active particle with a wall is similar to that of a car driving into a wall. The active particle will continue to exert a force into the colloids for some amount of time before sliding off or rotating away. The duration of a collision is controlled by the rotational diffusion and in large part determined by the geometry of the colloids. When the colloids are in contact, they form inner (concave) and outer (convex) regions (see the sketch in Fig. 1). The outer surfaces have positive curvature, and colliding particles can slide off rather quickly. The inner surfaces have negative curvature and can create a trap for the active particles which greatly increases the duration of a collision. Under certain volume fraction, the gradient in particle aggregation along the colloidal surface depends on not only activity but also crowder size. For small active particles with sufficient activity, particles primarily aggregate in the concave region, which gives rise to a net repulsion. Repulsion increases with the increment of active force, since larger activity corresponds to a higher effective temperature and stronger collisions from the concave surface, pushing the colloids apart. For large crowders, only a few particles can still cluster near the inner surface of the colloids, due to the limited area of the concave region. Alternatively, crowders are more likely to accumulate in the convex region, which finally becomes an overwhelming factor generating an attractive interaction force. Once the dominant population of active particles is in the convex region, the attractive interactions are determined by the striking force on the outer surface of the colloids. Increasing both $\sigma_a$ and $F_a$ implies a higher effective temperature $T_e$, which leads to an augment of striking force. Thus, we observe a more remarkable attraction with the increment of not only crowder size but also active force.

Furthermore, we would like to emphasize large crowder size effect on the the effective force as shown in Fig. 4. Here we see that, as $\sigma_a > 2.5$, $F_{\text{eff}}(r = \sigma_a)$ in all cases is purely attractive, even though the behaviors in passive bath and active bath are quite different. For $F_a = 0$ (see inset), the depletion force gradually tends to vanish as $\sigma_a$ increases. This large crowder size effect in a passive bath is associated to the so-called cage effect [73]. Passive crowders having large enough size will be essentially excluded or depleted from the volume occupied by the probed colloids, leading to negligible effective interactions. In contrast, attractive force in the presence of activity becomes more prominent with increasing crowder size. This indicates the caging phenomenon does not work in an active bath. As already mentioned, due to self-propulsion motion, active particles have the ability to persistently strike their outer surface, thus generating attractive interactions. Note that besides effective temperature $T_e$, which is originally derived from the effective diffusion coefficient of active particles [32], the strength of striking and the resultant attraction can be relevant to another important quantity, i.e., the persistence length of the self-propulsion, denoted as $L$. The persistence length characterizes the distance that active particle moves along the direction of its original orientation, given by $L = v_T \tau_c \sim F_a \sigma_a^3/3$. With increments of either $F_a$ or $\sigma_a$, active particle self-propelled distance will be enhanced. Under a small active force $F_a = 10$, with increasing $\sigma_a$, cage effect which excludes the crowders away from the colloids is strengthened, while the ability of active particles to strike the colloids becomes stronger. These two aspects can be competitive. While under larger active forces $F_a \geq 20$, the activity-induced attractive interactions are largely intensified and become the dominant factor. The persistence length $L$ of the activity particle is usually regarded as a proper measure for the self-propulsion ability of active particles. It is therefore illuminating to investigate the relationship between the attractive depletion force $F_{\text{eff}}$ and the persistence length $L$ in case of large crowder sizes. Figure 5 plots the absolute value of the attractive force $|F_{\text{eff}}|$ as a function of $L$. Very surprisingly, all data points collapsed into a nearly straight line, implying the effective force increases linearly with $L$. This result suggests that in large crowder size regime, attraction force can be directly measured by the dynamical persistence length of the bath active particle, rather than active force or crowder size.

Lastly, for convenience, we present a contour plot of the effective force in contact $F_{\text{eff}}(r = \sigma_a)$ in the parameter space of $F_a - \sigma_a$, prescribing $F_a$ in the scope of 0 to 50 and $\sigma_a$ taking values in between 0.5 to 4.0. Here, two distinct regimes are involved. One in the left corner (in red color) corresponds to the parameter condition of small $\sigma_a$ and large $F_a$, manifesting a repulsion regime with $F_{\text{eff}} > 0$; another refers to the attraction regime with $F_{\text{eff}} < 0$ (in blue color) in the remainder of the parameter space. The intermediate dashed line characterizes $F_{\text{eff}} = 0$, which provides the boundary separating the two classified regimes. Notice that there exist distinct transitions between repulsion and attraction, depicted by the vertical and
horizontal arrows respectively. On the one hand, as vertical arrow points out, in the case of small \( \sigma_u \), the depletion force encounters an attraction-to-repulsion transition with increasing \( \sigma \). As manifested, supposing \( \sigma_u = 1.0 \), as \( \sigma_a \) is less than 20, the depletion force is attractive. In such an attraction region, \( F_{\text{eff}} \) exhibits a nonmonotonic change with increasing activity. Compared with the passive value at \( \sigma_a = 0 \), the attractive force under small active force is slightly enhances. It reaches a maximum at \( \sigma_a \approx 10 \). After that, the attraction inversely decreases. Finally, as \( \sigma_a > 20 \), the effective force transits into the repulsion regime. The strength of the repulsion monotonically increases with \( \sigma_a \). On the other hand, as the horizontal arrow points out, on the premise of a large active force, a repulsion-to-attraction transition will occur with increasing crowder sizes. As already mentioned, such a transition can be ascribed to the competition of particle accumulation in concave and convex regions around the colloids. The profile depicted in Fig. 6 is feasible for us to estimate the condition of transition between repulsion and attraction in terms of the parameters concerning particle activity and size.

### B. Activity-crowding coupling effect

In the preceding subsection, we have clarified the activity-size effect on the effective depletion force on the passive colloids in an active bath. We find that both activity and crowder size are definitely crucial factors associated to the transition between repulsion and attraction, determined by the parameter condition of \( \sigma_a - \sigma_u \), as illustrated in Fig. 6. Note that the above analysis is performed under a fixed volume fraction \( \phi = 0.1 \) where the crowding aspect has not yet been unravelled. \( \phi \) can be another important variable characterizing the degree of crowdedness. Surely, the effective interaction is influenced by a coupling of activity and crowding, which manifests a nontrivial active bath effect. To emphasize such an issue, the following analyses are extended to involve different crowding and activity conditions. Here we also deal with a nonchiral bath.

Figure 7 presents the depletion force \( F_{\text{eff}}(\phi) \) as a function of distance \( (r - \sigma_c) / \sigma_a \) under various volume fraction \( \phi \). The active force and particle size are given to be \( F_a = 30 \) and \( \sigma_a = 1.0 \). Error bars correspond to one standard deviation.

We go forward to quantify the activity-crowding coupling effect. The specific value of the depletion force in contact, i.e., \( F_{\text{eff}}(r = \sigma_c) \) is adopted as a measure. Figure 8 displays \( F_{\text{eff}}(r = \sigma_c) \) as a function of volume fraction \( \phi \) under various active forces (crowder size is fixed at \( \sigma_a = 1.0 \)), where the attractive and repulsive regimes are included. In the passive case \( F_a = 0 \), the depletion force is attractive, and the strength of the force increases with \( \phi \). Introducing activity, a clear transition between attraction and repulsion can be observed. As \( F_a \) is small, such as \( F_a = 5 \) and 10, we see that the depletion force remains attractive in the whole range of \( \phi \). The strength of the force is apparently enhanced compared to the passive one. Nevertheless, as \( F_a \) further increases, such as \( F_a = 30 \) and 40, the depletion force demonstrates a clear crossover from repulsion regime in small \( \phi \) to attraction regime in large \( \phi \), indicating a very nontrivial activity-crowding coupling effect. Large activity can induce a primary aggregation in the inner

![Contour plot of the effective force in contact](image)

**FIG. 6.** Contour plot of the effective force in contact \( F_{\text{eff}} \) in parameter space \( F_a - \sigma_a \), where \( \phi = 0.1 \). Two regimes of repulsion (red-yellow) and attraction (blue) are shown. Dashed line is the boundary separating the two regimes. Two arrows represent the transitions between attraction and repulsion with varying active force and crowder size respectively.

![Scaled active depletion force](image)

**FIG. 7.** The scaled active depletion force \( F_{\text{eff}}(r) / F_a \) as a function of distance \( (r - \sigma_c) / \sigma_a \) under various volume fraction \( \phi \). The active force and particle size are given to be \( F_a = 30 \) and \( \sigma_a = 1.0 \). Error bars correspond to one standard deviation.
region of colloids which arises to a repulsive interaction. While along with the increment of concentration, the aggregation in the inner area is saturated. The outer region aggregation is continuously augmented and finally becomes an overwhelming factor, generating an attractive interaction. Moreover, with each increment of activity, the critical value of volume fraction increases, at which repulsion-attraction transition occurs. We see that the critical volume fraction for \( F_a = 30 \) locates at \( \phi \simeq 0.2 \) and that for \( F_a = 40 \) is about \( \phi \simeq 0.25 \). This observation hints at the competition between the activity-associated repulsion and crowding-induced attraction. It is natural that a more intensive crowding condition is necessary to balance the strengthened activity effect at larger \( F_a \).

Note that previous studies investigated the behavior of driven granular media and found that two fixed large intruder particles experience an effective force which extends from very short to long length scales \([74,75]\). The long-range force can change its sign from attraction to repulsion upon decreasing the volume fraction. The proposed mechanism was based on the induced differences between hydrodynamic fields (like density and pressure) in the gap and outside regions due to fluctuations, leading to repulsion at low densities and attraction when approaching the jamming transition density. This repulsion-to-attraction transition seems very similar to our observations under large activity. We would like to emphasize that the effective force in our model system due to the local activity effect as shown in the left column, as well as the fluctuation-induced long-range force in randomly driven granular fluids. As mentioned above, the competition between the activity-associated repulsion and crowding-induced attraction serves as a reasonable picture for the transition phenomenon. In a passive situation or under low activity, however, excluded volume effect becomes dominant, leading to a definitely attractive force in regardless of volume fraction.

To gain more insight into the transitions as elaborated above, we plot the density distribution of active particles (with \( \sigma_a = 1.0 \)) in the vicinity of the two passive colloids, as shown in Fig. 9. The influence of varying active force and volume fraction on the change of the distribution is investigated by examining the aggregations of particles in regions I and II as classified in Fig. 1. The subfigures in the left column of Fig. 9 display the distributions under different active forces at a given volume fraction \( \phi = 0.1 \), and those in the right column show the distributions under different volume fractions at a prescribed \( F_a = 30 \). Apparently, in all cases, active particles show prominent accumulations around the colloids. This is in accordance with the phenomenon reported in the literature that active particles tend to cluster near walls or angles when they move in a confined space \([76,77]\). \( F_a \) and \( \phi \) dramatically affect the aggregation behavior. First, regarding the activity effect as shown in the left column, as \( F_a \) increases, the ability of active particle to cluster in both regions is enhanced. This is because particles with larger activity undergo stronger self-propulsion motion and longer relaxation time to keep away from the surface area of the colloids. In order to quantify the relative aggregation degree, we evaluate the average volume fraction in regions I and II, denoted as \( \phi_I \) and \( \phi_{II} \) respectively. For \( F_a = 10 \), we obtain \( \phi_I = 0.107 \) and \( \phi_{II} = 0.118 \). \( \phi_{II} > \phi_I \) results in a net attractive force. With each increment of active force, we observe particles are more easily trapped and temporarily accumulated in the concave region I rather than in the convex region II. For \( F_a = 50 \), we obtain \( \phi_I = 0.198 \) and \( \phi_{II} = 0.136 \). \( \phi_I > \phi_{II} \) leads to a net repulsive force. Increasing activity strengthens the concave region aggregation and provides a brief picture of the attraction-to-repulsion transition.
Second, we take a look at the crowding effect on particle distribution from the subfigures in the right column. With each increment of $\phi$, the accumulation of particles near colloids (both inner and outer areas) is inevitably intensified. We analyze the average volume fraction in regions I and II. For lower bulk volume fraction $\phi = 0.1$, we have $\phi_I = 0.171$ and $\phi_{II} = 0.127$. As mentioned, particles under certain activity have priority to cluster in the more confined concave region. In the relatively dilute case, the accumulation in region I is thus more obvious. $\phi_I > \phi_{II}$ indicates a resultant net repulsive force. However, as crowdedness increases, the number of particles aggregating in the concave region gradually reaches a saturation. As a result, particles are alternatively promoted to cluster in the outside convex area. As displayed in Fig. 9 (bottom right column), in the concentrated situation $\phi = 0.3$, there appear clearcut packing circles near the outer surface of the colloids. In such a case, we have $\phi_I = 0.378$ and $\phi_{II} = 0.443$. $\phi_{II} > \phi_I$ indicates a net attraction force. The dramatic increment of aggregation in the convex region with increasing bulk volume fraction provides a reasonable understanding for crowding-induced repulsion-to-attraction transition.

Figure 10 presents a contour plot of the effective force in contact $F_{\text{eff}}(r = \sigma_a)$ in the parameter space of $F_a - \phi$ prescribing $F_a$ in the scope of 0 to 50, and $\phi$ taking values in between 0.1 to 0.3. The repulsion-attraction transition induced by the interplay between activity and crowding is well identified. Evidently, there appear two distinguishable regimes. One lies in large $F_a$ area (in red color), manifesting a repulsion regime with $F_{\text{eff}} > 0$; another falls in a small active force area (in blue color), displaying an attraction regime with $F_{\text{eff}} < 0$. The intermediate dashed line characterizes $F_{\text{eff}} = 0$, which provides the boundary separating the two classified regimes. Similar to that in Fig. 6, the transition between repulsion and attraction is clearly involved, depicted by the vertical and horizontal arrows respectively. On the one hand, as the vertical arrow points out, under a given $\phi$, depletion force encounters an attraction-to-repulsion transition with increasing $F_a$. The critical active force for the emergence of transition augments with volume fraction. For limited activity, the crowding effect is dominant. Thus, depletion interaction is attractive. Depletion force in attraction regime undergoes a nonmonotonic change with the increment of active force. It implies that activity in on a small scale strengthens the crowding effect induced attraction, while activity in on an intermediate scale inversely reduces such an effect. As $F_a$ further increases, repulsive interaction eventually becomes overwhelming, promoting the depletion force falling into the repulsion regime. Once $F_{\text{eff}}$ is repulsive, it monotonically increases with $F_a$. One the other hand, as the horizontal arrow points out, on the premise of a large active force, a repulsion-to-attraction transition will occur with increasing volume fraction. Apparently, such a transition can be ascribed to the competition between activity-associated repulsion and crowding-induced attraction. As $\phi$ is relatively small, activity effect is dominant, and thus the depletion force is repulsion. As the bath becomes more concentrated, the crowding effect increases, and finally becomes the principal factor promoting the depletion force falling into the attraction regime. The phase diagram shown in Fig. 10 serves as a useful guide to understand the activity-crowding coupling effect induced transition between repulsion and attraction.

Figure 11 reveals the nontrivial effective force transition under varying parameters of active force and volume fraction. The underlying activity-crowding coupling is understood under the condition of a fixed crowder size. As already demonstrated in Sec. III A, crowder size effect is crucial to influence the effective interactions. We thus extend our investigation to elucidate the activity-crowding coupling effect associated to diverse active crowder sizes. As a result, Fig. 11 presents the contour plot of $F_{\text{eff}}(r = \sigma_a)$ in the parameter space of $\sigma_a - \phi$ under a given active force $F_a = 50$. In a large $\sigma_a$ region, the crowding effect is dominant and depletion...
interaction is attractive. In the relatively small and moderately active crowder size region, a clearcut transition phenomenon between the two distinguishable regimes of repulsion and attraction is involved. As the vertical arrow points out, under a given $\phi$, depletion force encounters a repulsion-to-attraction crossover with increasing $\sigma_a$. The critical active crowder size for the emergence of attraction decreases with volume fraction. Meanwhile, according to the horizontal arrow, we see that under a given $\sigma_a$, effective force will also experience a transition from repulsion to attraction as volume fraction increases.

C. Chirality effect of active bath

In the above two subsections, we mainly focus on the active crowder size effect and activity-crowding coupling effect. The active particles are assumed to be nonchiral in the analyses. Now, we turn to investigate the depletion interactions in a bath of active particles with dynamic chirality, i.e., particles rotate with a deterministic angular velocity $\omega$ besides self-propulsion. Surely, dynamic motions of active particles with and without chirality follow different mechanisms. It can be expected that chirality can induce significant discrepancy in the aggregation behavior around the two probed passive colloids. As a consequence, in addition to active force, bath concentration, and particle diameter, chirality can be another important factor modulating the effective interactions. To emphasize such an issue, we will explicitly evaluate the depletion force in a chiral active bath, with variables including angular velocity $\omega$, active force $F_a$, and volume fraction $\phi$. For simplicity, the particle diameter is fixed at $\sigma_a = 1.0$; i.e., the particle size effect is omitted.

Note that chiral active particles are characterized by both angular velocity $\omega$ and active force $F_a$. $\omega$ influences the rotational motion $\theta(t)$ according to Eq. (4). Combined with Eq. (2), the translational motion $r(t)$ of active particles will be adjusted by their chiral feature through the active term $F_a \mathbf{n}(\theta)$. As a consequence, the effective interaction force induced by active particles will be a function of both $\omega$ and $F_a$. It is reasonable that chiral particles with larger activity can play a more prominent role. Thus, we mainly focus on examining the effect of chirality under the condition of large active forces. It is interesting to make clear to what degree the effective force can be modified by chirality of active particles.

First, we evaluate the variation of effective force with respect to the distance $r$ between the two passive colloids, i.e., $F_{\text{eff}}(r)$. We assume the angular velocity of bath particles is $\omega = \pi$. Two active forces are considered, i.e., $F_a = 30$ and $50$. The bath volume fraction is fixed at $\phi = 0.1$. Figure 12 shows the depletion force $F_{\text{eff}}(r)/F_a$ induced by chiral particles (solid lines) as a function of scaled distance $(r - \sigma_a)/\sigma_a$. The nonchiral ($\omega = 0$) counterparts are also plotted here (dashed line) for comparison. It is clear that the profiles for $\omega = \pi$ exhibit rather similar oscillatory behavior as that in case of nonchirality. Besides, the peak location of the oscillations and the range of interaction do not change much with both $F_a$ and $\omega$, while a clear reduction of the repulsive depletion force due to introduction of $\omega$ is manifested. Bath particles with large active force basically induce repulsive interactions. This is due to the aggregation of the particles in the inner region of the passive colloids. In the period of self-propulsion, a chiral active particle is also subject to a deterministic rotation, so that its ability of persistent motion is reduced. We suspect the accumulation behavior in chiral bath will be attenuated by chirality, resulting in weakened repulsive interactions.

The above analysis is performed at a given chirality $\omega = \pi$. It is meaningful for us to quantify extensively the effective force under varying $\omega$. In what follows, we mainly concern the effective force in contact, i.e., $F_{\text{eff}}(r = \sigma_a)$. Figure 13(a) displays the scaled effective force $F_{\text{eff}}(r = \sigma_a)/F_a$ as a function of $\omega$ under various active forces ranging from 20 to 50. The volume fraction is prescribed at $\phi = 0.1$. We see here that the effective force in a nonchiral bath with $\omega = 0$ (open symbols) is basically repulsive. Very strikingly, in a chiral bath, the effective force (solid symbols) demonstrates a prominent quasiperiodic oscillation behavior with respect to $\omega$. The alternations of the peaks and troughs is evident, in a period of about 0.5$\pi$. To understand the chirality-induced oscillation phenomenon, we remember the fact that the evolution of position of active particles should be affected by both active force and chirality, through the active term in Eq. (2), i.e., $F_a \mathbf{n}(\theta) = F_a (\cos(\theta), \sin(\theta))$. The associated effective interactions induced by active particles are determined by particle dynamic motion, for which the activity and chirality effect have been embodied in an explicit manner. We suspect the oscillation behavior of effective force can be very relevant to the trigonometric functions involved by the dynamic equation. Besides the oscillation behavior, we find that for $F_a = 30$, 40, and 50, the effective force in the whole range of $\omega$ remains repulsive, which indicates chirality in such a large activity situation cannot essentially alter the repulsive nature of the effective interactions induced by the active bath. In accordance with Fig. 12, the magnitude of the repulsion is obviously reduced due to the presence of chirality. In fact, the effective force at $\omega = 0.5\pi$ can be 40–50% smaller than that at $\omega = 0$. With increasing active force, the repulsion is
The scaled active depletion force in contact $F_{\text{eff}}(r = \sigma_c) / F_a$ as a function of angular velocity $\omega/\pi$ under various active forces $F_a$. Inset is the magnification for $F_a = 20$, which shows a clear oscillation between attraction and repulsion. (b) Dependence of the scaled volume fraction in region I (i.e., $\phi_I / \phi$) on angular velocity $\omega/\pi$. Active crowder size is $\sigma_c = 1.0$ and volume fraction is fixed at $\phi = 0.1$. Error bars correspond to one standard deviation.

FIG. 13. (a) The scaled active depletion force in contact $F_{\text{eff}}(r = \sigma_c) / F_a$ as a function of angular velocity $\omega/\pi$ under various active forces $F_a$. Inset is the magnification for $F_a = 20$, which shows a clear oscillation between attraction and repulsion. (b) Dependence of the scaled volume fraction in region I (i.e., $\phi_I / \phi$) on angular velocity $\omega/\pi$. Active crowder size is $\sigma_c = 1.0$ and volume fraction is fixed at $\phi = 0.1$. Error bars correspond to one standard deviation.

globally enhanced. The profiles for different active forces exhibit similar oscillation behavior, with the same period of the alternations of peaks and troughs.

Very interestingly, in the case of $F_a = 20$, the chirality effect becomes rather delicate. Starting from the repulsive force under $\omega = 0$, there appears to be a clear transition between repulsion and attraction as chirality is introduced. The transition continues and oscillates with $\omega$ (see the magnification in the inset). As already noticed, chirality feature of particles induces an attenuation of particle aggregation in the concave area of colloids (i.e., region I), and thus results in a reduced repulsive interaction force. Besides, chirality effect is quasiperiodic within limited influences. If activity is large enough, the aggregation in region I remains dominant. This is the very reason why we observe a global repulsive profile for $F_a \geq 30$ in the whole range of $\omega$. Nevertheless, as active force is moderate (say $F_a = 20$), the resultant repulsion force in a non-chiral environment is rather small, indicating the aggregation in region I is limited. In such a situation, introducing chirality, particles have less ability to continuously aggregate in region I. As an alternative, the accumulation in region II can become overwhelming and the effective force turns to be attractive. Under proper condition of $\omega$, transition from repulsion to attraction might occur. Moreover, owing to the quasiperiodic feature of chirality effect, the transition oscillates with varying $\omega$.

To better understand the oscillation phenomenon as depicted in Fig. 13(a), we go a little bit further to investigate how chirality affects the accumulation of active particles surrounding the passive colloids. In the literature, particle aggregation in concave or convex regions is usually adopted to understand the origin of repulsive or attractive forces, and even used to measure the repulsion-attraction transition condition [55,57]. In the case of nonchirality, particles with certain large activity prefer to aggregate near the concave gap of region I, which originates the repulsive effective forces. It is meaningful to quantify to what degree the averaged volume fraction in region I (i.e., $\phi_I$) varies with respect to particle angular velocity $\omega$. Figure 13(b) shows the ratio $\phi_I / \phi$ (with $\phi$ being the bulk volume fraction) as a function of $\omega$. Interestingly, we observe a very similar oscillation behavior as that of effective force, where peaks and troughs alternates in a same period of about 0.5$\pi$. Strictly speaking, the averaged volume fraction evaluated here cannot provide an explicit understanding for the effective force, since each swimmer in reality exerts different collision intensities on the colloid, even though we hope the synergetic behavior inferred from the profiles of $F_{\text{eff}}$ and $\phi_I$ is meaningful in some sense, which suggests that the oscillation of depletion force can be attributed to the oscillation of particle accumulation in region I. In addition, when comparing with the value in a nonchiral bath ($\omega = 0$), $\phi_I$ exhibits an apparent decrement as chirality is involved. Chiral active particles would have a reduced ability to strike the concave region of colloids and thus have less population in the interior area. Chirality-induced dilution of active particles in region I can be the basic reason for the declined repulsive force as manifested in Fig. 13(a).

We find that chirality effect is definitely a key factor in an active bath which induces the depletion force oscillates with $\omega$ through changing the accumulation of active particles. Crowding effect will also impact the aggregation of particles, thereby adjusting the effective interactions. To emphasize such an issue, our analysis is extended to involve different crowding conditions. Both effective force and the averaged volume fraction of particles in region I are examined under several bulk volume fractions $\phi$ and a fixed active force $F_a = 50$. Figures 14(a) and 14(b) display $F_{\text{eff}} / F_a$ and $\phi_I / \phi$ versus angular velocity $\omega$. The two quantities exhibit robust quasiperiodic oscillations as angular velocity is increasing. Whatever the volume fraction is, the peaks and troughs of oscillation are situated at the same angular velocity. Moreover, chirality brings into a clear modification to both $F_{\text{eff}}$ and $\phi_I$. As $\phi = 0.1$ and $0.2$, the effective force is basically repulsive, with its magnitude being declined by chirality. As the bath develops enough crowding (say $\phi = 0.3$), the effective force is globally attractive. Compared with a nonchiral bath, chirality evidently enhances the attractive interactions, in accordance with an evident decreasing $\phi_I$. In a moderate volume fraction $\phi = 0.28$, it is rather intriguing that the effective force encounters a transition between repulsion and attraction (see inset). Under such a crowding condition, the relative accumulation in inner region I can be comparable with that in outer region II. As chirality is introduced, since aggregation in region I is reduced, particles are promoted to gather in the outer area of the
colloids, inducing an attractive interaction force. Again, we would like to address that the robust oscillating effective force and the modified force strength can be well interpreted by the coordinating behavior of chirality-modulated aggregation in region I.

**IV. CONCLUDING REMARKS**

In the present work, we performed a systematic study for the effective interactions between two passive colloids suspended in a crowded and active bath, based on two-dimensional Langevin dynamics simulations. Our main purpose is to identify the tunable depletion force induced by active particles in terms of activity and crowding. In particular, we evaluate the effective force under various system parameters including active force $F_a$, crowder size $\sigma_a$, volume fraction $\phi$, and also chirality measured by angular velocity $\omega$. The aggregation behavior of particles in the vicinity of the colloids is also examined. The nontrivial effects of crowder size, activity-crowding coupling, and chirality are unravelled in detail.

First, we have made clear the crowder size effect on the effective force. We found that as $F_a$ is small, the effective force remains attractive, which slightly decreases with $\sigma_a$, indicating a dominating excluded volume effect. Small activity strengthens the attractive interactions by enhancing the effective temperature of the bath. In the large activity situation, we observed that a nontrivial repulsion-attraction transition occurs along with the increment of active particle size. Such a transition can be ascribed to the change of particle aggregation behavior tuned by active crowder size. Indeed, particles subject to large active force have strong ability to accumulate in the concave area of the colloids, thus providing repulsive interactions. As $\sigma_a$ is small, the activity-induced repulsion is dominating. With increasing particle size, due to the short-age of aggregation in the concave area of colloids, repulsion induced by activity and attraction due to excluded volume effect become comparable. In large crowder size cases, the aggregation in inner region becomes rather difficult. Particles alternatively strike the outer area, generating an attractive force. A contour plot is presented for the effective force in $F_a - \sigma_a$ parameter space, from which we can conveniently estimate the condition of transition between repulsion and attraction in terms of the parameters concerning particle activity and size. Furthermore, we verified that in the case of large crowder size, the attractive force can be well scaled by the persistence length of active particles. This finding reveals a very different scenario from that of the passive case. In a passive bath, as the particle is large, the excluded volume effect and the effective force are negligible, while in an active counterpart, large particles with certain activity have stronger self-propulsion and thus have stronger ability to strike the colloids from the outer side. Then, significant attractive interactions arise.

Second, we explicitly evaluated the coupling effect between activity and crowding. Similarly, at small $F_a$, the depletion force appears as attraction due to the dominating excluded volume effect. The attraction enhances with the increment of volume fraction. When $F_a$ is large, there is a clear activity-crowding competition effect on the effective force. In a relatively dilute situation, bath particles under certain activity are likely to accumulate in the concave region of the colloids, generating repulsive interactions. However, with increment of $\phi$, due to the saturation of particle cluster in concave region, more particles tend to strike the outer region of the colloids, providing attractive interactions. Thus, we observed a transition from repulsion to attraction with increasing $\phi$. The density distribution of active particles in the vicinity of colloids is evaluated to understand the transition. We observed a more concentrated gathering of particles in the concave region with increasing activity in the case of limited volume fraction, but a more concentrated gathering of particles in convex region with increasing $\phi$. We also presented a phase diagram for the effective force in $F_a - \phi$ parameter space, which is feasible for us to clarify the repulsion-to-attraction transition caused by activity-crowding coupling effect.

Finally, we examined the chirality effect on the depletion force by introducing the deterministic dynamical rotating characteristic into the particle motion equation. The large activity regime is particularly considered, for which the more prominent chirality effect is expected. Also, as already known, a nonchiral bath with large activity basically induces repulsive interactions. We investigated to what degree the effective force $F_{\text{eff}}$ can be modified by chirality. The depletion force $F_{\text{eff}}$ as a

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**FIG. 14.** (a) The scaled active depletion force in contact $F_{\text{eff}}(r = \sigma_a)/F_a$ as a function of angular velocity $\omega/\pi$ under various volume fractions $\phi$. Inset is the magnification for $\phi = 0.28$, which shows a clear oscillation between attraction and repulsion. (b) Dependence of the scaled volume fraction in region I (i.e., $\phi_I/\phi$) on angular velocity $\omega/\pi$. Active crowder size is $\sigma_a = 1.0$ and active force is fixed at $F_a = 50$. Error bars correspond to one standard deviation.
function of the angular velocity $\omega$ is quantified. Very surprisingly, results demonstrate a robust oscillation phenomenon. The alternations of the peaks and troughs is evident, in a period of $0.5\pi$ roughly. In order to gain the possible reason for such a peculiar behavior, the averaged volume fraction in the concave region I, i.e., $\phi_I$, is computed. Interestingly, we observed a very similar oscillation of $\phi_I$ with increasing $\omega$. Evidently, the quasiperiodic change of particle accumulation in region I tuned by chirality can provide the basic picture for the coordinate variation of the effective force. Moreover, compared with a nonchiral bath, we find the repulsive force in a chiral bath is slightly reduced, due to the weakened self-propulsion of active particles in the presence of chirality. In addition, we specifically analyzed the system with some critical parameters of active force or volume fraction, where the activity-induced repulsion and the crowding-induced attraction are competitive. We revealed a delicate oscillating transition between repulsion and attraction.

Note that in the present work, we limit ourselves to a simple model of monodisperse active bath; namely, the bath is composed of spherical active particles with uniform size and active force. Nevertheless, as is known, real biological systems such as cells are very complex environments in which the heterogeneous multicomponent mixtures, such as macromolecules of proteins, nucleic acids, carbohydrates, lipids, and small solutes, are enclosed in the confined space [78, 79]. Such real systems involve complex mixtures of different sizes, nonuniform activity, and even different shapes. The extension of our present study to analyze the active depletion force in a polydisperse environment is straightforward. We can expect the effective interaction mechanism determined by the interplay of excluded volume effect and activity effect will show complicated diversification depending on the mixture details. The comprehensive understanding of active depletion force in a polydisperse active and crowded bath is definitely a subject worth studying in the future.

The two-dimensional setup we used in the present work is realizable in experiments and relevant for biological systems, including membranes and interfaces. More simulations are necessary to understand the three-dimensional (3D) case. We suspect the essence of our results regarding attractive-repulsive transition should be extendable to a system with 3D confinement, while the underlying mechanism should be somewhat discrepant. This can be understood from a simple kinetic argument. There are two timescales that govern the system, namely the reorientation time and the mean collision time, which are related to the mean free path by active propulsion. The ratio between these timescales determines how likely particles are to be trapped in the surface area of the colloids. Since the orientational correlation time in 2D is twice as large as in 3D [80], particles in two dimensions with smaller active force already have ability to build up dynamical clustering, whereas for a three-dimensional system higher propulsion strengths are needed. The different degree of kinetic trapping and accumulation brings into significant deviations of active depletion force between 2D and 3D systems. The comprehensive analysis of effective force in more realistic three-dimensional active and crowded environments is desirable, which is a subject worth studying in the future.

The present study deepens our understanding of the active depletion force. Also, it provides a suggestive application for the tunable active depletion force by changing the bath conditions regarding not only activity but also particle size, crowding, and chirality.

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