Directed Assembly of Binary Magnetic Particles

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Introduction
The purpose of this project was to establish a model to quantify the pair interaction energy of systems composed of two magnetic anisotropic particles. The point dipole approximation is currently used to model the interactions of isotropic and anisotropic particles. We applied the anisotropic dipole model to quantify the pair dipolar interactions of binary systems composed of particles with different ellipsoidal shape. Results show that pair interactions between anisotropic particles can be tuned based on the particle shape, and we show the potential capabilities to generate assembled structures with different configurations, which can be applied in the production of biomimetic devices, materials with desired optical or electronic properties, and targeted drug delivery.

Model
The pair interaction energy is quantified by

\[ U_{ij} = -\beta \times (Mx_i \times Hr_j + My_i \times Hr_y + Mz_i \times Hr_z), \]
\[ U_{ji} = -\beta \times (Mx_j \times Hr_i + My_j \times Hr_y + Mz_j \times Hr_z), \]
\[ U_{dd} = U_{ij} + U_{ji}, \]

where \( U_{ij} \) is the interaction energy of particle J due to the field of particle I, \( U_{ji} \) is the interaction energy of particle I due to the field of particle J, \( U_{dd} \) is the pair dipolar interaction energy between particle I and J, \( H \) is the dipole field, \( M \) is the magnetic moment, and \( \beta \) is the interaction parameter defined as the ratio of magnetic to thermal energy. The interaction energy is plotted respect to particle relative position of particle j respect to particle I in the center.

Results
We analyzed particles with aspect ratios ranging from one to ten and with the second particle having an orientation ranging from zero to one hundred eighty degrees with respect to the major axis of the first particle (particle I). The minimum on the energy landscape is where the second particle (particle J) is mostly like to settle.

We combined the energy landscapes of particles of the same size in order to find the orientation and location of the energy minimum for two particles of aspect ratios. The y-axis is the angle of particle J, the x-axis shows the contact angle along the surface of particle I. The next figure shows the combined energy landscape for particles with aspect ratio \( r_2^I/r_m = 2.51 \), \( r_2^J/r_m = 3.16 \) and \( r_2^I/r_m = 5 \), \( r_2^J/r_m = 2 \). The last figure shows 3 combined energy landscapes with \( r_2^I/r_m \) increasing from 1 to 3.16 to 10 with \( r_2^J/r_m = 2.51 \).

Multi-particle Systems
We analyzed larger systems with up to a thousand particles with differing aspect ratios. We analyzed different interacting conditions between particles and field conditions. Preliminary results are shown in the next figures for a small system composed of 36 particles with an equal fraction number of particles with aspect ratios one and four. The arrow represents the direction of the applied field.

Conclusions
This model accurately describes the dipolar interaction energy of magnetic ellipsoids with different aspect ratio at and any angle. Additionally, the model matches the current literature on the dipolar interaction of spheres. Larger interaction parameter beta and aspect ratios can be used to control self-assembled equilibrium configurations. Furthermore, field magnitude and direction allows tunable configurations in directed assembly.

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