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Bursting microspheres by field-induced restructuring of magnetic aggregates

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Abstract

We use advanced quaternion molecular dynamics to demonstrate that microspheres, consisting of a stable membrane enclosing a fluid and a small number of magnetite particles, can be moved around and opened in a time-dependent inhomogeneous magnetic field. The destruction of the membrane is induced by the magnetic aggregate changing from a ring in zero field to a chain in a high field in case that the ring fits inside the membrane, whereas the chain does not. We discuss an intriguing application of this system in medicine, where a harmful substance is to be transported through blood vessels and released in a planned manner at a desired location in the body.

75.50.Mm, 75.40.Mg, 83.80.Gv, 83.10.Pp

There has been recently increased interest in aggregates of small magnetic particles such as those found in ferrofluids [1,2]. The magnetic particles, typically consisting of magnetite, have a typical diameter of few hundred Ångstroms, carry a large permanent magnetic moment of the order of magnitude $10^4 - 10^5\ \mu_B$, and are covered by an approximately 20 Å thick surfactant layer which prevents them from coalescing at room temperature in a viscous suspension. Spontaneous formation of complex labyrinthine [3] and branched [1] macroscopic structures has been observed and theoretically addressed [4–9] in these systems at low temperatures and in applied magnetic fields.

Of particular interest in this study is the fact that aggregates of $4 \lesssim n \lesssim 14$ magnetic tops are a classically tunable two-level system [10]. Their most stable structure in zero field is a ring, but they open to a chain when exposed to a large nonzero magnetic field [2]. In this contribution, we describe a possible application of this structural transition as a one-way valve causing liquid-filled microspheres to burst.

Microspheres have been used extensively in medicine as micro-containers that transport and deliver an active substance to a specific site in the human body. Their typical diameter of 0.1 μm is small enough to allow the microcapsules to pass through all capillary blood vessels. The most significant application of this technique is in the chemotherapy of cancer, since the most potent drugs are indiscriminately toxic to all tissue. Such substances should not come into contact with healthy tissue, and only be locally delivered in the tumor region.

The standard solution of this problem was to use albumin, polyalkylcyanoacrylate, ethylcellulose or polyglutaraldehyde for the membrane, that would safely contain the drug, yet biodegrade over time. Here we describe an alternate local drug delivery mechanism, based on the structural transition of an aggregate of magnetic tops, that allows to move the microspheres to a particular location and to deliver the active substance in a planned fashion using a time-dependent magnetic field [11].

The principle of the mechanism proposed is illustrated in Fig. 1. We propose to enclose several magnetic nanoparticles together with the active drug in the microcapsule. In zero or very low applied magnetic field these particles will aggregate to a ring that fits snugly in the

microcapsule [see Fig. 1(a)]. A low inhomogeneous magnetic field, such as used in magnetic resonance imaging, can be used to concentrate the microcapsules in a particular location. At this moment, application of a stronger magnetic field will cause the ring of magnetic tops to open up to a chain [2] [see Fig. 1(b)]. The imposed deformation of the cage will cause it to burst open, hence releasing the active substance at the desired location.

Of course, the response of the system to the environmental variables such as temperature and mangetic field is critical for the successful application of this technique. There is significant freedom in selecting the system parameters, such as the diameter of the microcapsules, their surface tension, the diameter and the permanent magnetic moment of the magnetic tops, the spatial variation and the strength of the externally applied magnetic field. In the following, we will describe the time evolution of such a microcapsule containing both molecules of an active substance and magnetic particles.

In our model, the outer shell of the microcapsule consists of a mesh of 272 particles, interacting with a Lennard-Jones type potential with equilibrium distance of 100 Å and a well depth of 0.1 eV. The near-spherical shape of the cage, shown in Fig. 2, results from the internal pressure due to the repulsion between the 100 enclosed molecules, and the repulsion between these molecules and the cage. A crucial component of the microsphere are six spherical magnetic tops of magnetite, with a diameter of 200 Å and a large permanent magnetic moment of 1.68×10^5 μ_B. The interaction between the magnetite particles is pairwise and governed by a nonmagnetic, essentially repulsive interaction, a dipole-dipole interaction between the particles themselves, and the interaction of the dipoles with an external magnetic field B_{ext} [2].

There are obviously various ways to understand the bursting of the microsphere due to the structural transition in the magnetite aggregate in a quantitative fashion. In the following, we will discuss the results of a molecular dynamics simulation for this system. We used quaternion molecular dynamics for a microcanonical ensemble that was optimized and equilibrated for the kinetic temperature of $\approx$300 K. We used a time step of 10^{-11} s and a fourth-order Runge-Kutta formalism to integrate the Euler-Lagrange equations to obtain

the trajectories of the particles [12]. Our simulations showed the system to be stable in zero field at room temperature.

Next, we applied a magnetic field of 25 Gauss, and followed the structural evolution for a total time of 40 ns. The results are shown in Fig. 2. The four consecutive snap shots illustrate the the time evolution of the bursting process. The first onset of the bursting can be seen already after 20 ns, where a single fluid particle (red) escapes from the microcapsule through a small hole in the cage. We then observe the hole size to increase very fast following the initial fracture. 40 ns following the application of the magnetic field all fluid particles escape from the cage and the microcapsule collapses.

In conclusion, we have presented an intriguing example of using the isomerisation of clusters to realize a mechanical switch on a microscopic scale. We can imagine that the same phenomenon should occur in transition metal clusters of few ($n \lesssim 20$)atoms, where the shape of the ground state isomer could change significantly in an applied magnetic field [13] and thus lead to the same effect as discussed above.

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and references therein.

FIGURES

FIG. 1. Schematic view of a microcapsule containing few magnetic tops and fluid in a membrane. (a) In zero field, the equilibrium structure of th tops is a ring that fits into a spherical membrane of radius R_0. (b) In nonzero field the ring opens up to a chain, thus deforming the membrane to an ellipsoid with the long axis R_1. The capsule will burst if $R_1 >> R_0$.

FIG. 2. Time evolution of the microsphere after its initial equilibration in zero field at time $t = 0$. Interatomic bonds in the membrane are shown by the white rods, and the fluid molecules by the small red spheres. The magnetite particles are represented by the large spheres and the orientation of their magnetic dipole by the north (blue) and south (yellow) hemispheres. The four snap shots of the geometry after switching on the magnetic field show an intact system at $t = 1\times10^{-8}$ s, beginning membrane fracture at $t = 2\times10^{-8}$ s, and the continuing collapse of the membrane, coupled with dispersion of the liquid, at $t = 3\times10^{-8}$ s and $t = 4\times10^{-8}$ s.

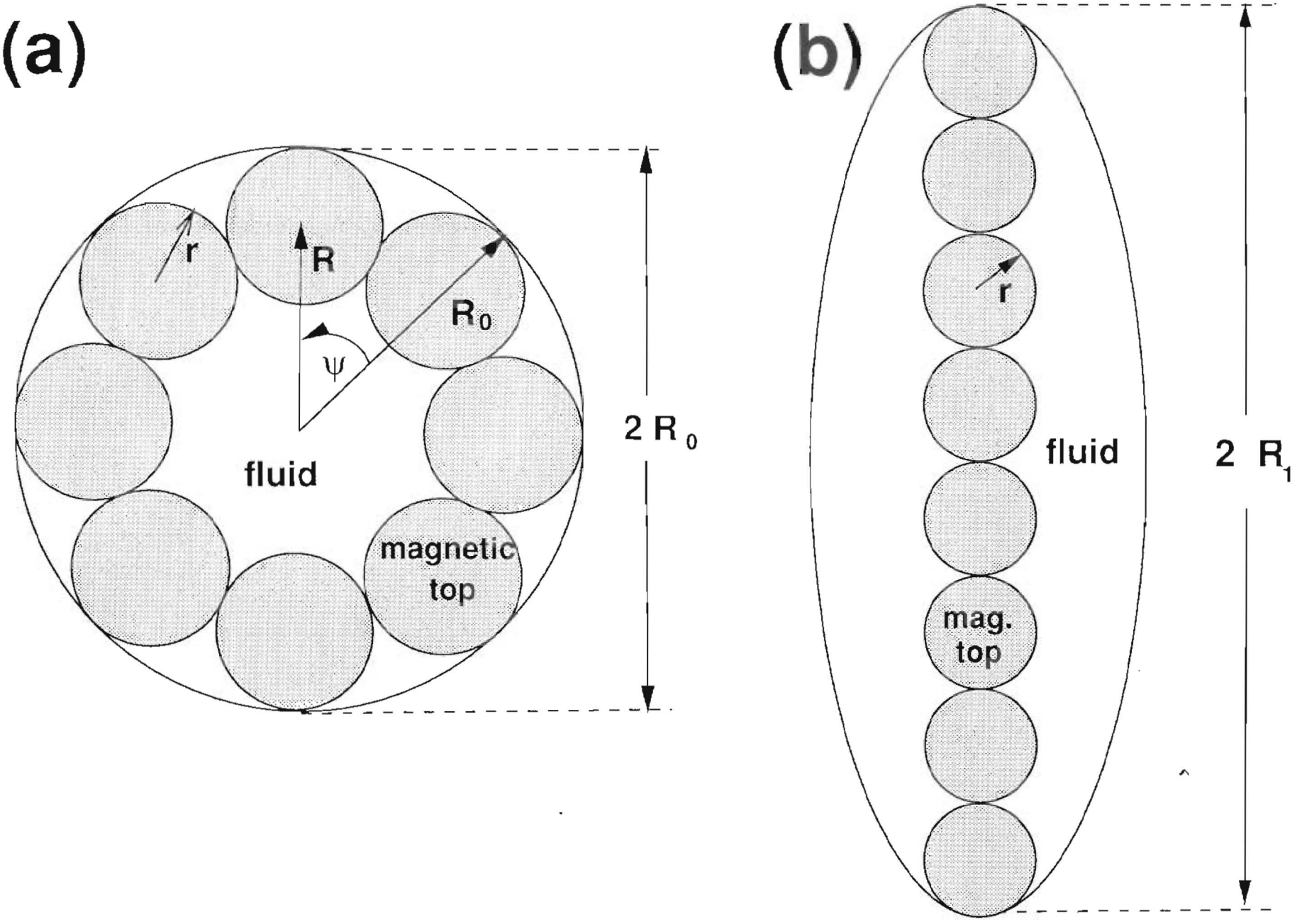

Figure 1

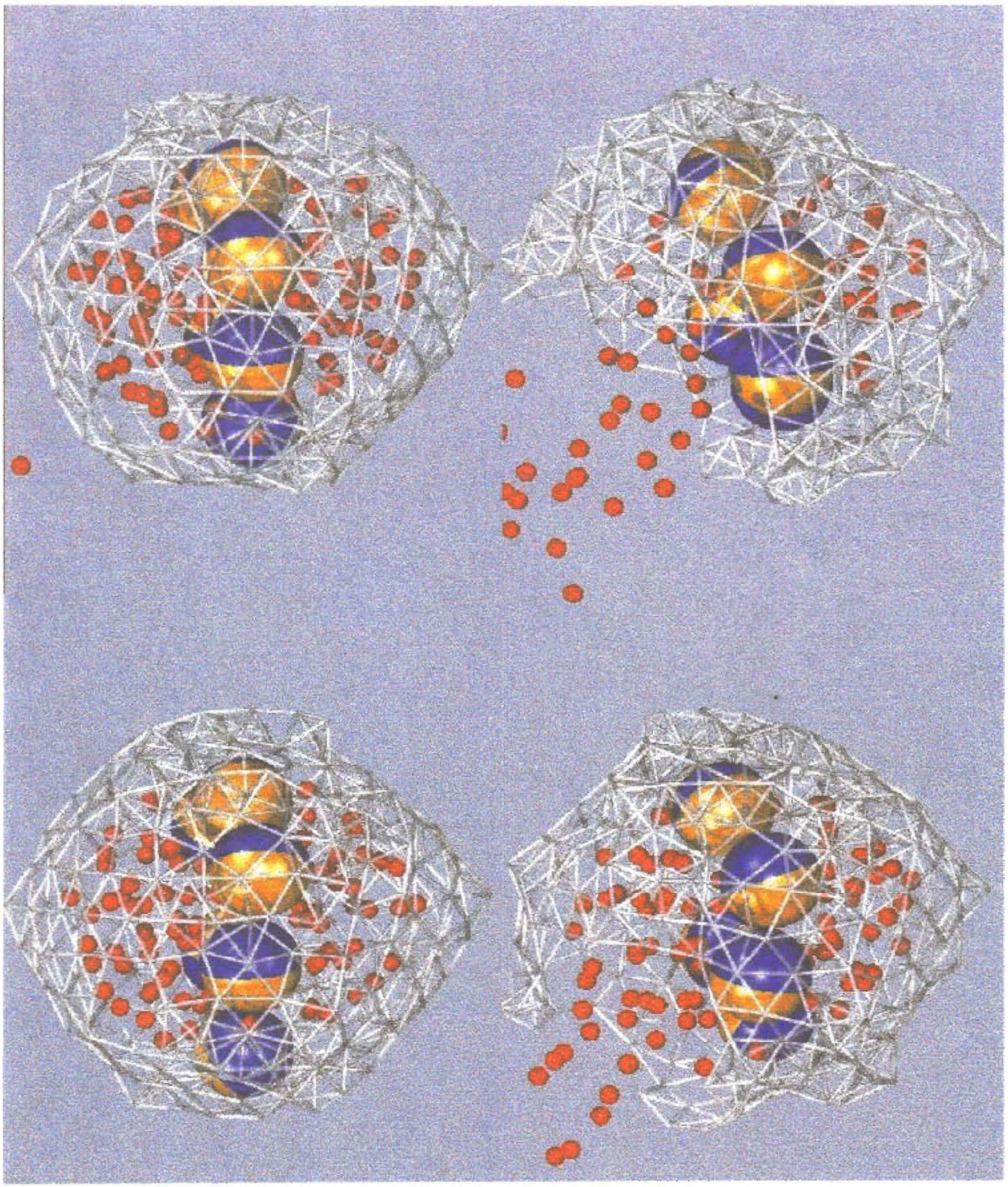

Fig. 2