LETTER

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Bohdan Senyuk[1,2], Qingkun Liu[1,3], Sailing He[3], Randall D. Kamien[4], Robert B. Kusner[5], Tom C. Lubensky[4] & Ivan I. Smalyukh[1,2,6]

Although a coffee mug and a doughnut look different to most of us, they are topologically equivalent solid tori or handlebodies of genus $g = 1$, both being different from, say, balls and solid cylinders of genus $g = 0$, to which they cannot be smoothly morphed without cutting[11,12]. In a similar way, molecules can form topologically distinct structures including rings, knots and other molecular configurations satisfying the constraints imposed by chemical bonds[24]. Although the topology of shapes, fields and defects is important in many phenomena and in theories ranging from the nature of elementary particles to early-Universe cosmology[25,26], topological aspects of colloidal systems (composed of particles larger than molecules and atoms but much smaller than the objects that we encounter in our everyday life) are rarely explored. Typically dealing with particles with surfaces homeomorphic to spheres, recent studies[8,9,15,18,20–23] demonstrate that the topology of curved surfaces dictates the formation of defects during two-dimensional colloidal crystallization at fluid interfaces as well as inside liquid crystal droplets and around spherical inclusions in liquid crystals. However, despite the fact that several techniques for scalable fabrication of particles with complex geometric shapes and $g > 0$ have recently been introduced[18,19,27–29], the potential impact of particle topology on colloidal alignment, self-assembly and response to fields remains unexplored.

To study the interplay of particle topology and defects in liquid crystals, we fabricated topologically distinct silica particles with planar symmetry and handlebody topology of genus g varying from 1 to 5; their surfaces had an Euler characteristic $\chi = 2 - 2g$ ranging from 0 to -8 (Fig. 1 and Supplementary Fig. 1). These particles had 1 μm × 1 μm rounded square cross-sections and ring diameters ranging from 5 to 10 μm. Handlebody particles were introduced into a nematic liquid

into point defects and vice versa by melting the liquid crystal into an isotropic state with tweezers of laser power more than 100 mW and subsequently quenching into a nematic phase, indicating that free energies due to director configurations with these defects are comparable. These hedgehog charges of the point defects and disclination loops have been determined by assuming that the vector field lines point perpendicularly outwards from the particle surfaces (Fig. 3) and by mapping the vector fields around particles, point defects and disclination loops onto the order-parameter space[31,32]. Because has non-polar symmetry (that is, is equivalent to −), one could have chosen the vector field pointing inwards to the surface of colloids, which would consequently reverse the signs of all hedgehog charges induced by particles in a uniformly aligned liquid crystal. The relative charges of all the defects would remain the same, as would the net charge of 0,

previously observed for the 'bubble gum' configurations formed around colloidal dimers[22].

We have characterized the Brownian motion of colloidal handlebodies (Fig. 4a–c). Their diffusion in a planar cell with thickness much larger than the diameter of the handlebody is highly anisotropic (Fig. 4a, d) and easier along $_0$ than perpendicular to it. The slopes of mean square particle displacements (MSDs), shown in Fig. 4a for a solid torus ($g = 1$), yield diffusion coefficients $D_x = 0.0023\,\mu m^2\,s^{-1}$ and $D_y = 0.0034\,\mu m^2\,s^{-1}$ measured normal and parallel to $_0$, respectively. Being oriented with respect to $_0$ (Fig. 4d), particles also experience angular thermal fluctuations (Fig. 4b) with $\langle \Delta\theta^2 \rangle$ of angular displacements (MSD_θ) initially increasing linearly with the lag time τ and then saturating as a result of the elasticity-mediated alignment. The width of the histogram distribution of the angle θ between the axis of revolution of the solid torus and $_0$ (Fig. 4b, inset) is 9.6×10^{-3}

substrates (Fig. 4e). However, because of slow rotation of the ring compared with the roughly 10-ms response time of ( ), an abrupt application of simply alters ( ) around the particle while preserving the initial particle alignment in the cell. For a solid torus (g = 1), this causes the original ( ) to transform into a topologically equivalent configuration with two disclination loops (Fig. 4f, g). Using different voltage-driving schemes, colloidal handlebodies and structures around them can be switched between the two bistable orientations and ( ) configurations shown in Fig 4d, f that are stable at no applied field. All observed transformations of (