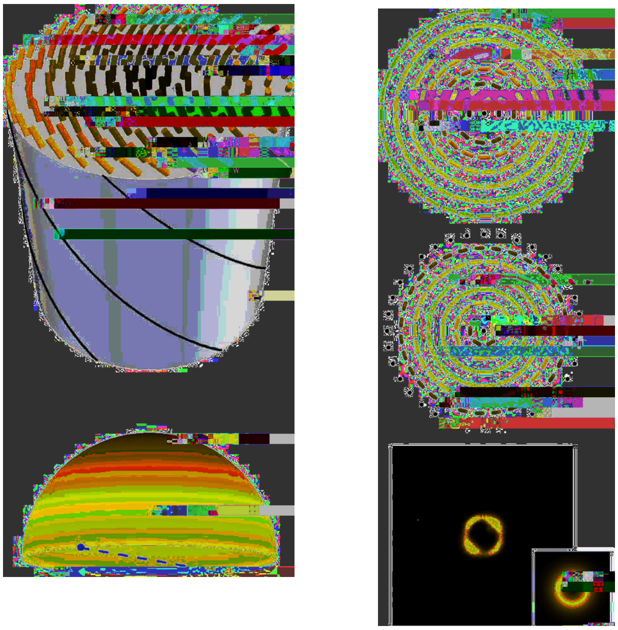
[9], although chiral condensed-matter systems so far have yielded realizations only of elementary full and fractional skyrmions. Here we describe stable, high-degree multi-skyrmion configurations where an arbitrary number of antiskyrmions are contained within a larger skyrmion. We call these structures skyrmion bags. We demonstrate them experimentally and numerically in liquid crystals and numerically in micromagnetic simulations either without or with magnetostatic effects. We find that skyrmion bags act like single skyrmions in pairwise interaction and under the influence of current in magnetic materials, and are thus an exciting proposition for topological magnetic storage and logic devices.

Skyrmions are particle-like topological excitations studied in many condensed-matter systems. For example, some of the earliest reports of liquid crystals (LCs) in the 1800s dealt with chiral phases in cholesterol derivatives extracted from animals, including the so-called 'blue phase'[10–12]. Decades later, these phases were demonstrated to be arrays of fractional skyrmions (also called 'merons'), cubic and hexagonal lattices of double-twist tubes in molecular alignment described by the director field $\mathbf{n}(\mathbf{x})$ with non-polar head–tail symmetry[7,12]. The rod-like molecules in such a tube are arranged to be parallel to its axis at its centre, twisting radially outwards to form barber-pole-like patterns on concentric cylindrical surfaces (Fig. 1a–c). Elementary full LC skyrmion tubes, with such a 180° radial twist from the centre to the periphery[5,6], exhibit all possible molecular orientations, can be embedded in a uniform far-field background and enjoy topological protection (Fig. 1d,i and Supplementary Fig. 1). In a simply connected manifold, a smooth director structure can always be vectorized and gives a smooth vector configuration (compare Fig. 1c,d with Fig. 1h,i), a process in which the order parameter space changes from $\mathbb{S}^2 / \mathbb{Z}_2$ to S^2 (Fig. 1b,g). Therefore, a large number of topologically equivalent solitonic structures have been observed and exhibit similar behaviour in LCs and other condensed-matter systems, such as magnets.

The vectorized field can be in two antiparallel orientations and be given topological degrees Q with opposite signs[13]. Here we adopt the convention $Q = -1$ for an elementary full skyrmion in Fig. 1i[14].

The discovery of similar skyrmion configurations in the magne-



By the convention that the arrows are oriented (0, 0, 1) away from the skyrmion centre, an elementary full skyrmion has degree −1 (ref. [14]). Inside a stretched skyrmion, the arrows are oriented (0, 0, −1), and an antiskyrmion placed here has degree +1. Hence, the total degree of an $S(N_A)$ bag is $N_A - 1$ (agreeing with our configurations up to numerical precision). More complex structures with antiskyrmion bags inside skyrmion bags have been experimentally and numerically realized too (Supplementary Fig. 4), giving a net degree $N_A - N_S$, which can in principle be any integer, positive or negative, where N_S is the total number of skyrmions and counting both N_S and N_A includes the both skyrmion and antiskyrmion bags.

We predict that 2D skyrmion bags will also exist in solid-state chiral magnets. The energy density equation (1) is a good description of oriented chiral materials more generally and represents a micromagnetic Hamiltonian (see Methods). We perform dynamical simulations of magnetic skyrmion bags based on the energy density in equation (1) and the Landau–Lifshitz–Gilbert equation using the MuMax3 finite-difference GPU accelerated code[22]. For magnetic systems, J and D describe the exchange and Dzyaloshinskii–Moriya interaction (DMI)[23–26], where f_{ext} incorporates Zeeman coupling, magnetostatic energy and magnetocrystalline anisotropy terms. The skyrmion bags in chiral magnets can be stabilized by an applied magnetic field (Fig. 3a), which leads to the conformational difference compared to their LC counterparts, albeit with identical topology. The effect of including the magnetostatic energy is illustrated in Fig. 3b, where the demagnetizing field acts as an easy-plane helical wavelength[23]. Therefore, the inter-skyrmion distance serves as a good measure of stability in skyrmion bags.

Magnetic skyrmion bags have potential in racetrack memory

Methods

LC experiments and simulations. *Materials and sample preparation.* To ensure accessibility and a broad impact of our work, pentylcyanobiphenyl (5CB, from EM chemicals) and a low-birefringence nematic mixture ZLI-3412 (EM Chemicals), commonly used and commercially available nematic LC materials, were doped with small amounts of chiral additives, cholesterol pelargonate (Sigma-Aldrich) or CB-15 (EM Chemicals), resulting in le -handed or right-handed chiral nematic LCs. e material parameters of 5CB and ZLI-3412 are listed in Table 1. e helicoidal pitch p of the LC mixture is determined by $p=(\xi \cdot c)^{-1}$, where c is the weight fraction of the additive and ξ is the helical twisting power of the additive. Con ning glass substrates were treated with polyimide SE1211 (Nissan Chemicals) to ensure vertical alignment of LCs at the LC/glass interface. Polyimide was applied to substrates by spin-coating at 2,700 r.p.m. for 30 s and then baked for 5 min at 90 °C and then 1 h at 180 °C. LC cells with gap thickness of $d=10$–$20\,\mu$m were produced by sandwiching glass bre segments in ultraviolet-curable glue. In cells where $d/p\approx 1$, spontaneous and controllably generated structures corresponding to minima of free energy were generated and manipulated using laser tweezers, as detailed below.