Supplementary Information for Direct observation and dynamics of spontaneous skyrmion-like magnetic domains in a ferromagnet

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Origin of large clusters
To our knowledge, there has been no real-space observation of magnetic clusters above the Curie temperature $T_C$, because the cluster is too small to be detected by LTEM\(^1\). However, the observed cluster unanticipatedly exhibits largeness. This can be explained in the context of Griffiths’ theory\(^2\). The cluster arises from an inherent random potential by quenched disorder (QD), namely, when perovskite A-sites are in solid solution (chemical disorder), and $T_C$ decreases as QD is enhanced\(^3,5\). In $T_C < T < T_G$, where $T_C$ and $T_G$ are the Curie temperatures in the presence and absence of QD, respectively, the existence of the FM bond is given by the probability $p$ ($\leq 1$), which is equivalent to the disorder parameter ($p = 1.0$ represents the absence of QD). The existence probability of clusters with an arbitrarily size $V$ is given by $p^V$. The present sample is under ideal conditions for the appearance of large clusters that can be detect by LTEM with $p$ ($T_C \approx 300$ K, $T_G \approx 350$ K) larger than that of other manganites such as Nd\(_{0.5}\)Ba\(_{0.5}\)MnO\(_3\) ($T_C \approx 140$ K, $T_G \approx 300$ K)\(^4\).

Peanut-shaped cluster
We also considered the other type of spin configuration for the peanut-shaped cluster. The out-of-plane magnetizations at the two vortex centers are considered to be antiparallel, as shown in Fig. S1. Contrary to the parallel case (Fig. 2h), the antiparallel case cannot smoothly connect the exteriors of the two vortices, as shown in the encircled area.
**Figure S1 | Other spin structure model of the peanut-shaped cluster.** In contrast to Fig. 2h, the magnetization directions of the two centers are antiparallel. The white circle is inserted to emphasize the spin configurations outside the two vortices.

**Supplementary Movies**

**Movie S1 | Dynamics of single cluster at 310 K.** The observation was taken by the Fresnel method with an underfocus of $\Delta f = -0.3$ mm. The bright and dark dot contrasts indicate the CW and CCW vortices, respectively.

**Movie S2 | Dynamic coupling of spacially-closed clusters at 360.8 K.** The observation was taken by Fresnel method with an underfocus of $\Delta f = -0.4$ mm.

**References**