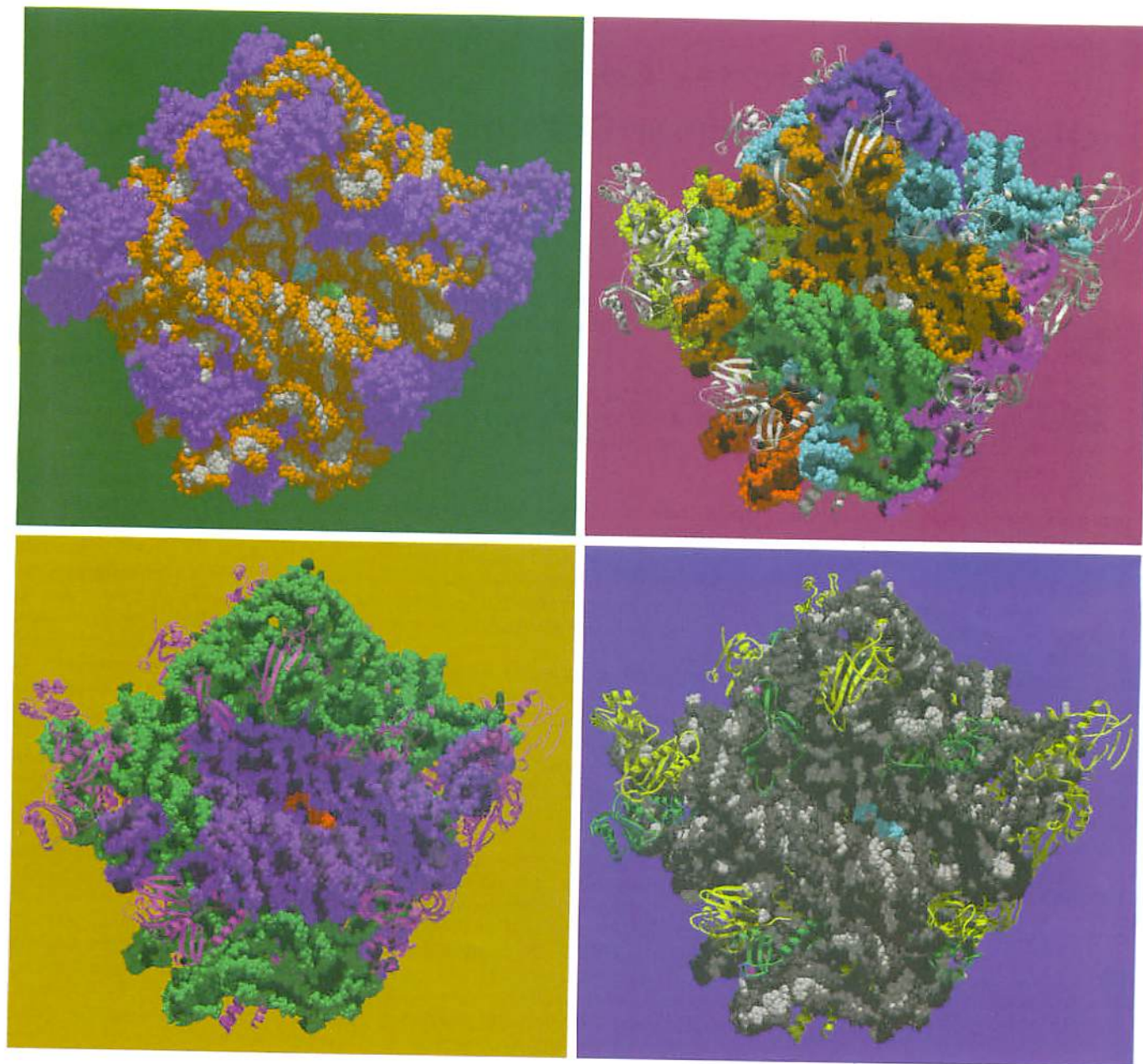


Reprint Series

Science

11 August 2000

Vol. 289 No. 5481
Pages 821-1096 \$8



AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

COVER Four representations looking into the active site cleft of the large ribosomal subunit of *Haloarcula*. Synthesis of peptide bonds is catalyzed by ribosomal RNA in the active site, which contains the aminoacyl ends of the transfer RNAs (in contrasting colors). Clockwise from upper left: RNA (orange and white) and protein (blue), RNA domains coded by color, conserved proteins (yellow), and universally conserved RNA structure (blue). [Images: P. Nissen *et al.*]

Magnetic Vortex Core Observation in Circular Dots of Permalloy

T. Shinjo,^{1*} T. Okuno,¹ R. Hassdorf,^{1†} K. Shigeto,¹ T. Ono²

Spin structures of nanoscale magnetic dots are the subject of increasing scientific effort, as the confinement of spins imposed by the geometrical restrictions makes these structures comparable to some internal characteristic length scales of the magnet. For a vortex (a ferromagnetic dot with a curling magnetic structure), a spot of perpendicular magnetization has been theoretically predicted to exist at the center of the vortex. Experimental evidence for this magnetization spot is provided by magnetic force microscopy imaging of circular dots of permalloy ($\text{Ni}_{80}\text{Fe}_{20}$) 0.3 to 1 micrometer in diameter and 50 nanometers thick.

Ferromagnetic materials generally form domain structures to reduce their magnetostatic energy. In very small ferromagnetic systems, however, the formation of domain walls is not energetically favored. Specifically, in a dot of ferromagnetic material of micrometer or submicrometer size, a curling spin configuration—that is, a magnetization vortex (Fig. 1)—has been proposed to occur in place of domains. When the dot thickness becomes much smaller than the dot diameter, usually all spins tend to align in-plane. In the curling configuration, the spin directions change gradually in-plane so as not to lose too much exchange energy, but to cancel the total dipole energy. In the vicinity of the dot center, the angle between adjacent spins then becomes increasingly larger when the spin directions remain confined in-plane. Therefore, at the core of the vortex structure, the magnetization within a small spot will turn out-of-plane and parallel to the plane normal. Although the concept of such a magnetic vortex with a turned-up magnetization core has been introduced in many textbooks (1), direct experimental evidence for this phenomenon has been lacking.

Recent model calculations for a Heisenberg spin system of $32 \times 32 \times 8$ spins in size (2) indicate that a curling spin structure is realized even for a dot of square shape, where a spot with turned-up magnetization normal to the plane exists at the center of the vortex (Fig. 1). The simulations, which are based on a discrete-update Monte Carlo method described elsewhere (3), take account of exchange and dipole energies while neglecting anisotropy. Further, they show that no out-of-plane component of the magnetization occurs if the dot thickness becomes too small. On the other hand, when the thickness exceeds a certain limit, the top and bottom spin layers will tend to cancel each other, and again no perpendicular magnetization should be observed. A vortex core with perpendicular magnetization is therefore expected to appear if the shape, size, and thickness of the dot are all

appropriate, and the anisotropy energy may be neglected.

A number of experiments have been carried out to study nanoscale magnetic systems. Cowburn *et al.* reported magneto-optical measurements on nanoscale supermalloy ($\text{Ni}_{80}\text{Fe}_{14}\text{Mo}_6$) dot arrays (4). From the profiles of the hysteresis loops, they concluded that a collinear-type single-domain phase is stabilized in dots with diameters smaller than a critical value (about 100 nm) and that a vortex phase likely occurs in dots with larger diameters. However, the authors were not able to obtain direct information on the spin structure in each dot. As suggested by theoretical calculations, the size of the perpendicular magnetization spot at the vortex core should be fairly small, and hence conventional magnetization measurements should fail to distinguish a fraction of perpendicular magnetization from the surrounding vortex magnetic structure.

In this context, we report magnetic force microscopy (MFM) measurements on circular dots of permalloy ($\text{Ni}_{80}\text{Fe}_{20}$) that give clear evidence for the existence of a vortex spin structure with perpendicular magnetization core. Samples of ferromagnetic dots were prepared by means of electron-beam lithography and evaporation in an ultrahigh vacuum using an electron-beam gun. The desired patterns were defined on thermally oxidized Si substrates capped by a layer of resist and subsequently topped by a layer of permalloy. By a lift-off process, the resist is removed and permalloy dots with designed sizes remain on top of the Si surface. The thickness of the circular dots reported here is 50 nm; the diameter of the dots was varied from 0.1 to 1 μm . In MFM, the instrument was operated in ac mode to detect the magnetic force acting between the cantilever tip and the surface of the permalloy dots. A low-moment ferromagnetic tip of CoCr was used to minimize the effect of stray fields. The distance between tip and sample surface was set to 80 nm on average. Sample scans

¹Institute for Chemical Research, Kyoto University, Uji 611-0011, Japan. ²Faculty of Science and Technology, Keio University, Yokohama 223-8522, Japan.

*To whom correspondence should be addressed. E-mail: shinjo@scl.kyoto-u.ac.jp

†Present address: Research Center Caesar, D-53111 Bonn, Germany.

Fig. 1. Monte Carlo simulation for a ferromagnetic Heisenberg spin structure comprising $32 \times 32 \times 8$ spins [courtesy of Ohshima *et al.* (2)]. (A) Top surface layer. (B) Cross-section view through the center. Beside the center, the spins are oriented almost perpendicular to the drawing plane, jutting out of the plane to the right and into the plane to the left, respectively. These figures represent snapshots of the fluctuating spin structure and are therefore not symmetric with respect to the center. The structure should become symmetric by time averaging.

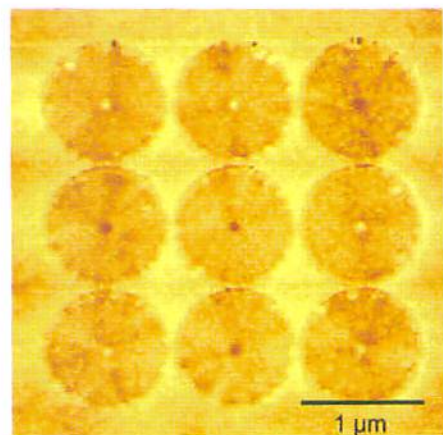
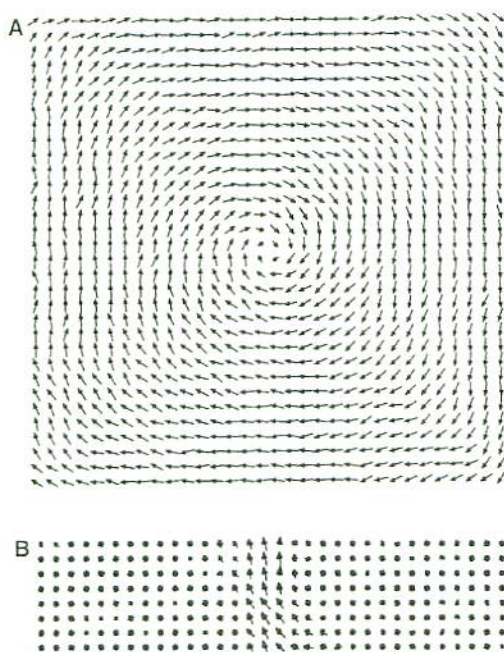


Fig. 2. MFM image of an array of permalloy dots 1 μm in diameter and 50 nm thick.

were taken in air at ambient temperature. An MFM image of an array of 3×3 dots of permalloy 1 μm in diameter and 50 nm thick is shown in Fig. 2. For a thin film of permalloy, the magnetic easy axis typically has an in-plane orientation. If a permalloy dot has a single domain structure or shows a domain pattern, in MFM a pair of magnetic poles reflected by a dark and white contrast should be observed in either case. In fact, the image shows a clearly contrasted spot at the center of each dot. It is suggested that each dot has a curling magnetic structure and the spots observed at the center of the dots correspond to the area where the magnetization is aligned parallel to the plane normal. However, the direction of the magnetization at the center seems to turn ran-

domly, either up or down, as reflected by the different contrast of the center spots. This seems to be reasonable, as up- and down-magnetizations are energetically equivalent without an external applied field and do not depend on the vortex orientation (clockwise or counterclockwise). The image shows simultaneously that the dot structures are of high quality and that the anisotropy effective in each dot is negligibly small, which is a necessary condition to realize a curling magnetic structure. (The spots in Fig. 2 around the circumference of each dot are artifacts caused by the surface profile, mainly resulting from unremoved fractions of the resist layer.)

MFM scans were also taken for an ensemble of permalloy dots with varying diameters, nominally from 0.1 to 1 μm (Fig. 3). These images were taken after applying an external field of 1.5 T along an in-plane direction (Fig. 3A) and parallel to the plane normal (Fig. 3B). For dots larger than 0.3 μm in diameter, a contrast spot at the center of each dot can be distinguished, and thus the existence of vortices with a core of perpendicular magnetization is confirmed. Again, the two types of vortex core with up- and down-magnetization are observed (Fig. 3A). In contrast, after applying an external field parallel to the plane normal, all center spots exhibit the same contrast (Fig. 3B), indicating that all the vortex core magnetizations have been oriented into the field direction.

From the above results, there is no doubt that the contrast spots observed at the center of each permalloy dot correspond to the turned-up magnetization of a vortex core. Although the vortex core is almost exactly located at the center of the dot, its real diameter cannot be estimated from the contrast spot observed by MFM, as this is below the lateral resolution power of this technique. To resolve a vortex core by MFM, it is necessary to pin the position of the core so that it is not affected by a stray field from the tip. In the experiments reported above, the vortex cores apparently have been so stable that a clear contrast appears in the MFM imaging process. Magnetic vortices are novel nanoscale magnetic systems, and it will be of great importance in the near future to study the dynamical behavior of turned-up and turned-down magnetizations, that is, fluctuations of the vortex cores.

References and Notes

1. See, for example, A. Hubert and R. Schäfer, *Magnetic Domains* (Springer, Berlin, 1998).
2. M. Ohshima, N. Suzuki, F. Matsubara, unpublished data.
3. J. Sasaki and F. Matsubara, *J. Phys. Soc. Jpn.* **66**, 2138 (1997).
4. R. P. Cowburn, D. K. Koltsov, A. O. Adeyeye, M. E. Welland, D. M. Tricker, *Phys. Rev. Lett.* **83**, 1042 (1999).

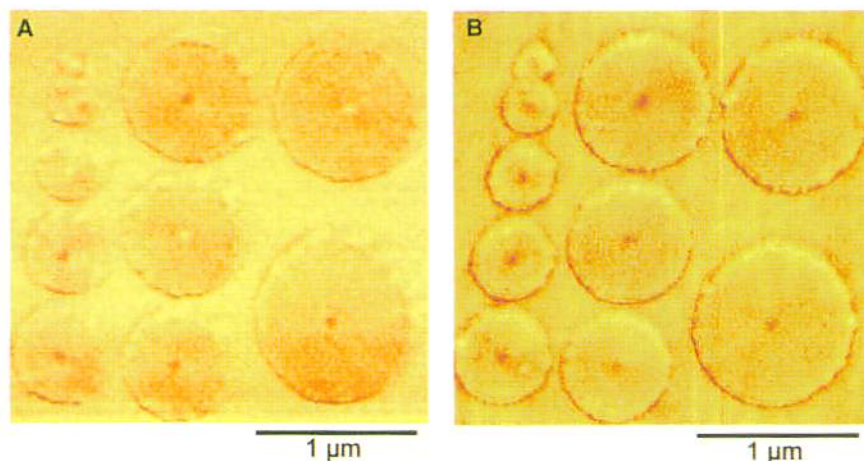


Fig. 3. MFM image of an ensemble of 50-nm-thick permalloy dots with diameters varying from 0.1 to 1 μm after applying an external field of 1.5 T along an in-plane direction (A) and parallel to the plane normal (B).

5. We thank F. Matsubara, N. Suzuki, and M. Ohshima for permission to reproduce one of their figures before publication, and Y. Suzuki, P. Beauvillain, J. Miltat, A. Thiaville, N. Hosoi, K. Mibu, S. Isoda, and H.

Miyajima for valuable discussions. Supported by a Grant-in-Aid for Creative Basic Research from Monbusho, by the New Energy and Industrial Technology Development Organization (NEDO), and by a Japan

Society for the Promotion of Science (JSPS) postdoctoral fellowship (R.H.).

8 March 2000; accepted 14 June 2000