surrounding shallow-water masses and are not efficient relative to direct sequestration of C on sinking particles to the deep ocean. We do not know whether the bloom eventually led to substantially higher C export after we left, or whether organic matter was remineralized within the surface ocean, resulting in no additional impact on C sequestration.

We have shown that iron addition to the Southern Ocean had a measurable impact on POC export, with flux increases observed not only within the iron-fertilized waters but also below the mixed layer in the "shadow" of the SOFeX patch. However, the magnitude of this flux increase was small relative to that of natural blooms in this region, or as needed to reduce current increases in atmospheric CO_2. To more accurately scale this flux response to iron as delivered in past climate cycles via dust or in proposed greenhouse mitigation schemes would require longer observations, comparisons between single versus multiple iron additions, deeper flux measurements, and larger patch scales to minimize artifacts due to dilution effects.

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Robotic Observations of Enhanced Carbon Biomass and Export at 55°S During SOFeX

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Autonomous floats profiling in high-nitrate low-silicate waters of the Southern Ocean observed carbon biomass variability and carbon exported to depths of 100 m during the 2002 Southern Ocean Iron Experiment (SOFeX) to detect the effects of iron fertilization of surface water there. Control and "in-patch" measurements documented a greater than fourfold enhancement of carbon biomass in the iron-amended waters. Carbon export through 100 m increased two- to sixfold as the patch subducted below a front. The molar ratio of iron added to carbon exported ranged between 10^4 and 10^5. The biomass buildup and export were much higher than expected for iron-amended low-silicate waters.

The Southern Ocean plays a critical role in the global carbon cycle and in the regulation of levels of atmospheric CO_2 (*1–3*), yet the biological and physical processes that sequester carbon remain poorly understood largely because of the difficulties in making observations in waters surrounding Antarctica. The January to February 2002 SOFeX (*4*) was designed to examine the biological and carbon system response to the effects of purposeful addition of iron to nitrate-rich waters north and south of the Polar Front Zone (PFZ). Iron was added to two ~225 km^2 regions near 55°S 172°W and 66°S 172°W to test the hypothesis that the lack of dissolved silicate would limit both biomass growth and carbon export. Waters north and south of the PFZ had dissolved nitrate:silicate concentrations of 22:2.5 μM and 27:60 μM, respectively. The "North Patch" at 55°S was considered to be silicate limiting.

Three free-profiling robotic Lagrangian Carbon Explorers (*5*) were deployed at 55°S from the research vessel (RV) *Roger Revelle* to provide high-frequency (three times per day) profile observations of particulate organic carbon (POC) (*6*), Temperature (T) and Salinity (S) in the upper 1000 m; a fourth was deployed at 66°S. Between profiles, the SOFeX Explorers were "parked" at 100-m depth to investigate the systematics of carbon export at 100 m with an optically derived carbon flux index (CFI) (*7*).

Our "control" Carbon Explorer 1177 (*8*) was deployed ~20 km north of the planned North Patch location on 11 January 2002; it drifted northeast parallel to bathymetry as expected for the Antarctic Circumpolar Current. Two Explorers were deployed "in the patch" (Fig. 1A). Explorer 2054 was deployed on 12 January in the planned center of the North Patch; the first infusion of iron immediately followed. Explorer 2054 immediately tracked to the northwest, reflecting a current shear that soon split the initial 15 km by 15 km iron-fertilized patch in two. The northwest segment of the iron-fertilized water was sampled by Explorer 2054, and enhanced biomass levels were traced for 14 days; subsequent biomass profiles were typical of those observed by the control float. This segment was never sampled by SOFeX ships again. Explorer 2104 was deployed on 19 January (patch day 7) just prior to a second Fe infusion to the other "half" of the North Patch (*9*). It advected to the northeast on a course that closely paralleled that of the control (Fig. 1A). We refer to Explorer 2104 as the "in-patch" Explorer.

Over the following three weeks, the control (1177) and in-patch (2104) Explorers tracked each other closely, while relaying their surfacing positions, hydrography, and carbon mea-

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surements in real time by satellite. Analysis of remotely sensed (QuikSCAT) winds and retrieved surface solar irradiance (*6*) indicated that both Explorers sampled biological systems that had experienced nearly identical surface physical forcing. Winds averaged 9 m/sec (range 4 to 16 m/sec). Virtually no difference in T and S structure of the euphotic zones was observed by the two floats (*6*).

The single cloud-free ocean color image of waters near 55°S showed that the North Patch had strung out into a 4-km-wide by 250-km-long filament by patch day 21 (*4*, *10*). Both the control and in-patch Explorers had drifted nearly 200 km with the Antarctic Circumpolar Current. One week later, RV *Revelle* returned to the North Patch on 8 February 2002 (patch day 27) with the aid of the in-patch Explorer Global Positioning System (GPS) positions. *Revelle* survey and conductivity-temperature-depth (CTD) data confirmed that the in-patch Explorer was "in," but not perfectly in, the southwest segment of the narrow filamentous North Patch (*6*) of iron-amended, low-silica, high-nitrate water.

The in-patch Explorer recorded a greater than fourfold increase in POC concentration in the upper 50 m from ~2 μM to ~9 μM over 4 weeks, whereas records from the control Explorer showed little change (Figs. 1 and 2) (*11*). From patch days 29 to 31, the POC maximum abruptly shifted from the surface layer to below 30 m, so that surface biomass actually decreased 2 days after the third iron amendment. In deeper waters at about the same time, the 1-μM POC isoline began a stepwise deepening, going from ~120 m to ~180 m by patch day 41; the control Explorer's record showed little evidence of change in POC.

The subduction of POC began with a change in surface stratification, which coincided with the appearance of a layer of ~0.3 degree warmer water near the surface (little salinity difference was observed). The particle-rich waters were extruded into a much thinned ~20-m layer. The warm layer thus became the "mixed layer" (*12*), and the iron-stimulated biomass was suddenly isolated from the surface in an environment with less than 10% of previously available photosynthetically active radiation and very much reduced levels of turbulence (*6*). The POC enhancement near 50 m was last observed on UTC day 65 (patch day 53), almost 2 months after the experiment began.

The time series of CFI showed little difference between control and in-patch observations before patch day 26. One day later and 21 days after the second iron infusion (and just before a third infusion of Fe), the in-patch CFI observations at 100 m began to show indications of an export event in progress (Fig. 2) that was not mirrored by the control. High-CFI events were observed episodically at an interval of 2 to 3 days and peaked 2 weeks later on patch day 41. The shift in upper water column stratification and the subduction of POC-rich waters began on patch day 29. It appeared that each high-CFI event was coincident with or preceded the stepwise deepening of POC isolines. Such POC isoline deepening and high-CFI events are indications of rapidly sinking particles and, hence, carbon export.

Because of the complicated dynamics of the patch and the Lagrangian nature of the Explorer sampling, either temporal or spatial variability in carbon flux could lead to observations of episodic high carbon flux. A hypothesis that the rain of particles was episodic and that the in-patch Explorer was sampling all the episodes would yield a lower limit on the integrated carbon flux. A hypothesis that the Explorer was having "transient encounters" with a continuous rain of particles from the narrow filamentous patch would require interpolation of the CFI between encounters and yield an upper limit for the carbon flux in the filamentous patch. There is some merit to considering this latter view, because the settling velocity of exported particles (100 to 200 m d^{-1}) is small compared with expected horizontal motions as the patch was subducted; thus, it is unlikely that such particles would take a purely vertical trajectory between 50 m and 100 m (*13*). Integration over 50 days of CFI data for control and in-patch Explorers using these assumptions show a twofold and a five- to sixfold enhancement of sedimentation below iron-amended waters for the lower and upper limits, respectively.

Carbon export estimates from shallow sediment traps or thorium methods are not available at 55°S for a direct calibration of the CFI. However, a calibration of the CFI was possible using thorium-based carbon export rates at 66°S (*14*). CFI to carbon export factors of 89 to 58 counts d^{-1} (mmol C m^{-2} $d^{-1})^{-1}$ were derived (*15*). Extrapolations of previous sediment trap data (*16*) to 100 m (*17*) and comparison with control Explorer's CFI record at 55°S yielded similar results (*18*). Directly applying the two possible 66°S CFI calibration factors to the 55°S CFI records between days 39 and 55 yields a lower limit on net export enhancement of 120 to 190 mmol C m^{-2} for the "episodic rain" hypothesis and an upper limit of 760 to 1170 mmol C m^{-2} for the "transient encounter" hypothesis. POC standing stock changes, if translated into export, indicate loss rates of 280 to 340 mmol C m^{-2} (*19*), but this estimate is also a lower limit.

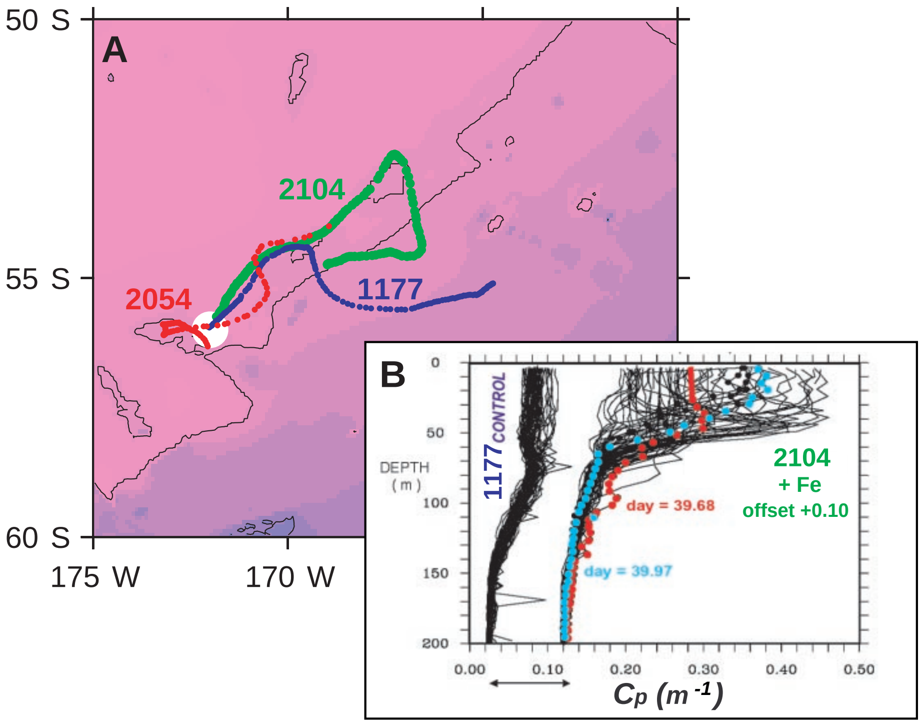

Fig. 1. (**A**) Trajectories of Carbon Explorers for the first 60 days of deployment superimposed over bathymetry of the Southern Ocean. Blue, red, and green tracks denote trajectories for Explorers 1177 (control), 2054 (in-patch #1), and 2104 (in-patch #2), respectively. (**B**) Carbon Explorer POC sensor data (beam attenuation coefficient) from the control (1177) and in-patch (2104) Explorers during the first month of observations of the North Patch. Three profiles per day were transmitted in real time. The highlighted profiles from the in-patch Explorer on universal time coordinated (UTC) day 39 were collected 6 hours apart at the time of the RV *Revelle* survey and indicate variable sampling of waters below 80 m that were enriched in POC. Both 1177 and 2104 went on to operate for another year in the Southern Ocean.

The Explorer data allows a first particle-based estimate of the ratio of Fe-added to POC-exported, as illustrated below. The original patch area was ~225 km^2, and the three amendments totaled ~1700 kg of Fe (*4*). The initial iron-fertilized patch (650 kg of Fe added) split in two, and half was lost from the experiment; thus, there was a net Fe amendment of ~1400 kg. From the only clear-sky satellite image available, the amended patch was approximately 1000 km^2 on patch day 21 (*4*, *10*), 6 days before the start of the sedimentation event and 10 days before the subduction event. During this subduction process, the layer containing the iron-enhanced biomass, between potential density surfaces of 26.6 and 26.5, decreased from a thickness of 40 m to approximately 20 m (Fig. 2 and fig. S11). We therefore hypothesize that the patch area doubled early during the sedimentation event, as required by water mass conservation. Applying the Explorer observations to a 2000-km^2 area yields an iron-added:POC-exported ratio (in moles) ranging from a lower limit of ~1:1×10^4 to ~1:1×10^5 at 55°S. These export estimates could increase by 40% if the third (450 kg) Fe addition (patch day 28) had no effect.

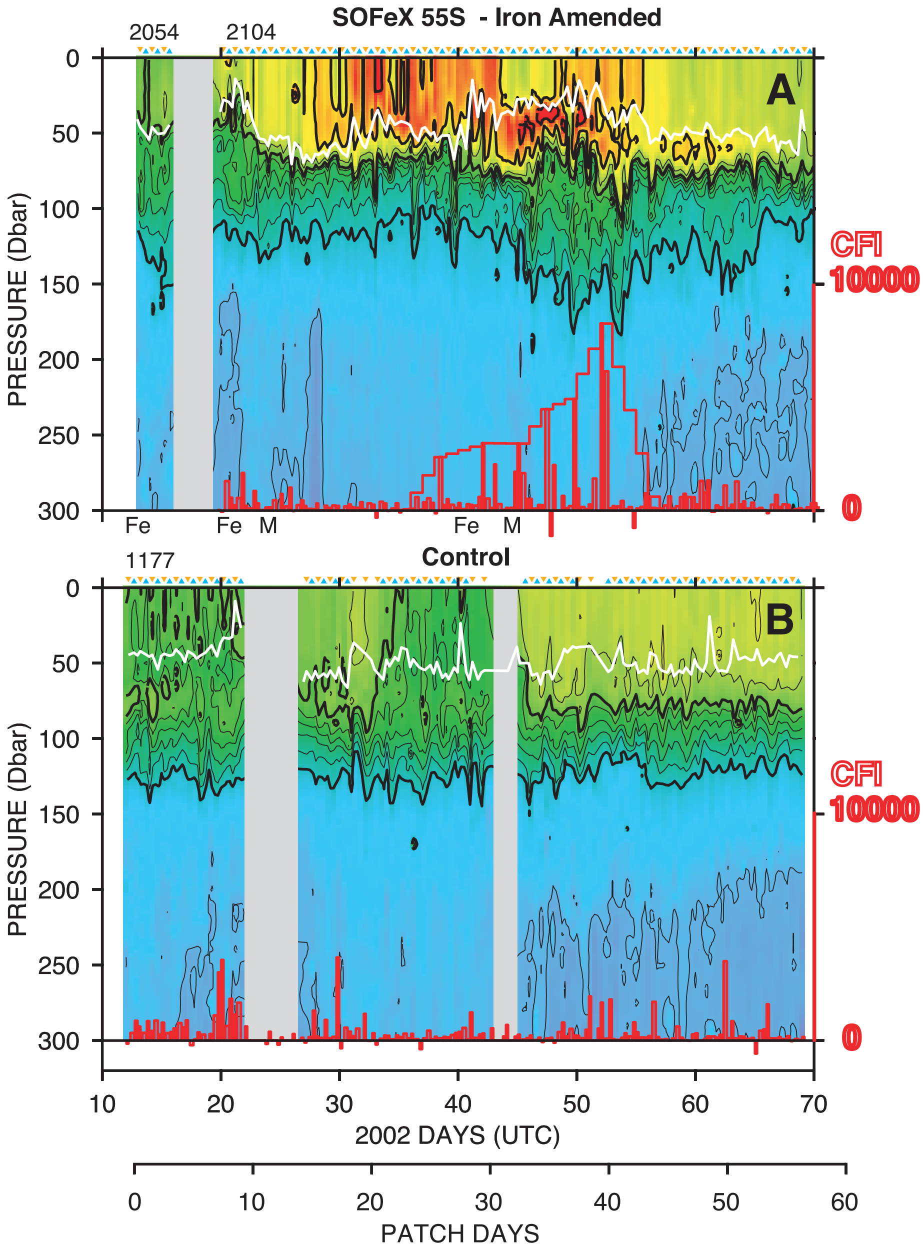

Fig. 2. Time series of POC variability from (**A**) Carbon Explorer 2104 (in iron-amended waters) and (**B**) Explorer 1177 (control) during the first 60 days of deployment. Patch day 0, the start of iron addition, corresponds to UTC day 12.5. The first week of data from Explorer 2054 is included in (A). Cyan up-triangle and orange down-triangle at the top of each panel are plotted at the times of dawn and dusk profiles, respectively. Heavy black contours for cold to warm colors are drawn at 1.0, 2.0, 4.0, and 8.0 μM POC levels. Light contours are at 0.5 μM intervals up to 2.5 μM (except between 1.0 μM and 2.0 μM, where they are drawn at 0.2 μM intervals). Near-surface lows in POC concentration recorded by the "in-patch" Explorer (e.g., UTC days 30 and 34) indicated that it was not always "in" the patch. The white curve is the mixed-layer depth, calculated from the dawn Carbon Explorer profile with potential density data (*12*). The red line plotted relative to the scale to the right of the figure is the carbon flux index (CFI) (counts d^{-1}) at 100 m. CFI values peaked UTC day 53 (patch day 41). About 150 POC profiles are represented in each of the time series shown. Gray bars are due to loss of profile data caused by transmit buffer overflow on the Explorer as a result of prolonged stormy conditions. CFI data are more frequent because they are transmitted at higher priority. *Revelle* was present at 55°S from 10 to 20 January and for a brief 2-day period in early February 2002. Times of Fe addition by RV *Revelle* are indicated by Fe. RV *Melville* (M) was present for several days during late January 2002 and again briefly in the third week of February 2002.

Phytoplankton present in the waters of the Southern Ocean have the highest iron stress in the world (*20*) and thus are most likely to respond to added iron (*21*). Iron fertilization experiments in the Southern Ocean have previously documented the stimulation of phytoplankton biomass after the addition of iron (*22*, *23*), but none of the experiments observed the end of the iron-stimulated blooms. SOFeX is the first experiment where the study of carbon export has been attempted on a sustained basis. Buesseler *et al.* (*14*) followed the export from the 66°S patch over 30 days. The Carbon Explorers at 55°S recorded patch events for ~50 days.

The SOFeX "ensemble" experiment tested the hypothesis that silica limitation would result in much less biomass enhancement and carbon export at 55°S compared with the silica-rich waters at 66°S. Our finding of a strong biomass increase in low-silicate, high-nitrate waters at 55°S contradicts the hypothesis and is confirmed by other shipboard data (*4*). We believe that the enhanced carbon export at 55°S was due to physical triggering (suddenly changed light/turbulence regimes), but we cannot rule out a natural progression of biogeochemical processes brought on by the third addition of iron and caution that extrapolation of these first results to greater depths or larger scales is premature.

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7. CFI is the measure of the accumulation of particles on the upward-looking optical (detector end) window of the Explorer's transmissometer-based POC sensor (WETLabs Inc., Philomath, OR) while the float is "parked" at 100 m. Before profiling starts, the raw transmission "counts" from the POC sensor are read;

then, the exhaust from the Explorer's pumped CTD removes settled particles and the transmission counts are read again. The difference between "after" and "before" readings divided by the time that the Explorer was parked at depth gives the CFI (counts/day). More detail, including pictures of instrument setup, is found in (*6*).

8. The serial numbers of the Explorers are assigned by the Scripps Instrument Development Group; we retain these identities because they uniquely identify the data sets underlying this paper. For simplicity, we refer to Explorer 1177 as the "control" Explorer and Explorer 2104 as the "in-patch" Explorer. Explorers 2054 and 2103 were also deployed "in patch" at 55°S and 66°S, respectively. The POC sensor on Explorer 2054 had a start-up problem that precluded CFI results; poor data transmission success resulted in only sporadic profile data (29 profiles in 2 months). The first week of 2054's profile data is combined with the time series from 2104 in Fig. 2A. Data from 2054 beginning 2 weeks after its deployment no longer showed evidence of the iron-enhanced biomass. Explorers 1177 and 2104 operated for more than 14 months; Explorer 2103, deployed at 66°S, last communicated on 23 July 2003, 18 months after deployment.
9. Retrospective analysis shows that Explorer 2104 was deployed 8 km north of the Monterey Bay Aquarium Research Institute's "center" drifter and near the north edge of the second patch laid down by R/V Revelle. In the coordinate system of Explorer 2104, it was deployed approximately 7 km west of the second Fe patch and ~8 km north of the drifter. The float, however, was deployed in waters containing SF6 and immediately registered higher POC levels. During Revelle's second visit to the North Patch in early February 2002, the float was "in" the narrow feature (*6*).
10. Moderate Resolution Imaging Spectroradiometer (MODIS) satellite image of surface chlorophyll was provided by F. Chavez and is described in (*4*).
11. Two pairs of Carbon Explorers operating in high-nutrient, low chlorophyll waters of the subarctic North Pacific in 2001 and 2003 yielded virtually identical biomass records over much longer periods (*5*, *24*) and thus provide confidence in the differences described here.
12. Mixed-layer depth is the depth where seawater potential density is increased by 0.05 units relative to the surface value.
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15. Carbon export through 100 m beneath the patch at 66°S was estimated using a one-dimensional Th-234 versus U-238 disequilibrium model (*14*). Values increased from ~3 (average of "in" and "out" patch day zero values) to 12 mmol C m^{-2} d^{-1} between 24 January and 21 February 2002 (UTC days 24 to 52; patch days 0 to 28). Buesseler *et al.* (*14*) interpret Th-234–based carbon export estimates as reflecting time scales of "several days to weeks"; thus, a comparison of CFI records averaged over "week" time scales is appropriate. At 66°S, Carbon Explorer 2103's CFI values from 5 to 14 February (UTC days 36 to 45; patch days 12 to 23) averaged 800 counts d^{-1} (SE = 350 counts d^{-1}; $n = 9$). Eliminating the first CFI reading yielded an average of 518 counts d^{-1} (SE = 138 counts d^{-1}; $n = 8$). The Th-234–based carbon export linearly interpolated to the time of the Explorer data = 9 mmol C m^{-2} d^{-1}. CFI of 800 counts d^{-1} divided by 9 mmol C m^{-2} d^{-1} = 89 counts d^{-1} (mmol C m^{-2} d^{-1})$^{-1}$; similarly, the 8-day averaged result = 58 counts d^{-1} (mmol C m^{-2} d^{-1})$^{-1}$.
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18. At 55°S, SOFeX Th-234 export estimates were not possible because of sparse ship coverage. Here, we can compare the average of the 2-month control Explorer (1177) CFI values with 1000-m sediment trap results for the same season and location but different year, reported by Honjo *et al.* (*17*). Carbon-flux estimates from Honjo *et al.* are extrapolated upward to 100 m using the Martin *et al.* (*19*) relationship. Depending on which set of three 17-day-long trap samples are used, we get conversion factors ranging from 50 to 80 counts (mmol C m^{-2})$^{-1}$. Given these similar values but recognizing the uncertainty of calibration, we apply 66°S CFI calibration factors of 58 and 89 counts (mmol C m^{-2})$^{-1}$ to 55°S CFI data.
19. Standing stocks of POC changed from about 9 to 2 mmol C m^{-3} over the export period. Assuming that the layer originally was ~40 m thick, we get a net loss of POC = 7 mmol m^{-3} × 40 m = 280 mmol C m^{-2}. POC loss estimated using profile data reported by Coale *et al.* (North patch RV *Revelle* station 32; rosette-collected water samples filtered through Whatman GFF filters) yields a difference of 8.5 mmol m^{-3} × 40 m = 340 mmol C m^{-2}. These calculations assume no net production of POC over the 2-week period of the loss and thus represent lowest estimates.
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Vortex Core–Driven Magnetization Dynamics

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Time-resolved x-ray imaging shows that the magnetization dynamics of a micron-sized pattern containing a ferromagnetic vortex is determined by its handedness, or chirality. The out-of-plane magnetization in the nanometer-scale vortex core induces a three-dimensional handedness in the planar magnetic structure, leading to a precessional motion of the core parallel to a subnanosecond field pulse. The core velocity was an order of magnitude higher than expected from the static susceptibility. These results demonstrate that handedness, already well known to be important in biological systems, plays an important role in the dynamics of microscopic magnets.

Magnetic films of a thickness below the magnetic exchange length form planar magnetic structures. Generally, the magnetization of such films is forced into the sample plane by the magnetic shape anisotropy. An exception to this rule is the magnetic vortex, a magnetic curl that appears at the intersection of Néel walls and in crosstie walls. Recent microscopic experiments have shown—as theory has long predicted—that vortices are three-dimensional structures that possess nanometer-sized cores in which the curling magnetization turns out-of-plane, avoiding the high energetic cost of anti-aligned moments (*1*, *2*). For data storage purposes, magnetic vortices can be trapped in lithographically defined, rectangular or circular magnetic patterns. They are of considerable technological interest, because the low magnetic stray field leads to a high magnetic stability and minimizes the cross-talk between adjacent vortices—two prerequisites for high integration density. We demonstrate that the out-of-plane magnetization in the nanometer-scale vortex core dominates the nanosecond magnetization dynamics of micron-sized vortex patterns. The observed gyrotropic motion of the vortex core around the pattern center corresponds to a subgigahertz mode seen in micromagnetic simulations and recent magneto-optical experiments (*3*–*6*).

Ultrafast techniques generally use pulsed optical lasers in a pump-probe arrangement (*7*, *8*). Although very high time resolution can be achieved, the spatial resolution of optical experiments is diffraction-limited by the wavelength of light to ~400 nm. This limitation can be overcome by x-ray imaging techniques. X-ray magnetic circular and linear dichroism (XMCD and XMLD) at the transition metal L edges probe the direction and size of the element-specific magnetic

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