

Nonvolatile Electric Control of Antiferromagnetic States on Nanosecond Timescales

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Electrical manipulation of antiferromagnetic (AFM) states, a cornerstone of AFM spintronics, is a great challenge, requiring novel material platforms. Here we report the full control over AFM states by voltage pulses in the insulating Co_3O_4 spinel well below its Néel temperature. We show that the strong linear magnetoelectric effect is fully governed by the orientation of the Néel vector. As a unique feature of Co_3O_4 , the magnetoelectric energy can easily overcome the weak magnetocrystalline anisotropy; thus, the Néel vector can be manipulated on demand, either rotated smoothly or reversed suddenly, by combined electric and magnetic fields. We achieve the nonvolatile switching within a few tens of nanoseconds between time-reversed AFM states in macroscopic volumes by voltage pulses. These observations render quasicubic antiferromagnets, like Co_3O_4 , an ideal platform for the ultrafast (picosecond to nanosecond) manipulation of microscopic AFM domains and may pave the way for the realization of AFM spintronic devices.

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Introduction—Ferromagnets still represent an important material platform for magnetic storage and spintronic devices [1,2]. However, they limit further miniaturization and speedup of these devices due to several drawbacks, such as the crosstalking between adjacent units via their stray fields, high sensitivity to external magnetic fields, and relatively slow spin dynamics [3,4].

Though antiferromagnets are free from these limitations, their applicability has not been put into consideration for long. Even Louis Néel stated in his Nobel lecture that antiferromagnets had no practical importance [5]. Contradicting his prediction, a plethora of recent studies imply that antiferromagnets can be viable replacements for ferromagnets in spintronic devices [3,4,6,7]. Emergent phenomena in antiferromagnets, such as anisotropic magnetoresistance [8,9], spin Hall effect [10–12], spin Seebeck effects [13–15], Néel spin-orbit torque [16,17], ultrafast terahertz manipulation of antiferromagnetic (AFM) spin waves [18], and dynamics of AFM skyrmions [19–22],

open up new opportunities in spintronics. AFM spintronics, which is a fast growing field at the frontiers of magnetism and electronics, is foreseen to trigger a change of paradigm in information technology [3,4,6,23].

Recently, electrical manipulation of AFM domains has attracted much attention, as a possible route to write and read information in AFM devices [3,4,7,24–29]. Spin-orbit coupling plays a key role in controlling the orientation of the AFM Néel vector ($\mathbf{L}$) in itinerant and insulating antiferromagnets via electric currents and voltages, respectively [30]. In noncentrosymmetric AFM metals, like CuMnAs [17], Mn_2Au [31], and $\text{Fe}_{1/3}\text{NbS}_2$ [32], current induced rotation of $\mathbf{L}$ is governed by spin-orbit torque and has led to the realization of first prototype of AFM random access memories (RAM). In noncentrosymmetric AFM insulators, such as Cr_2O_3 [33,34], LiCoPO_4 [35–38], and MnTiO_3 [39,40], the linear magnetoelectric (ME) effect can be exploited for electric field-driven switching of AFM domains, as a working principle for AFM-ME RAM [41]. While voltage-driven switching of $\mathbf{L}$ has an advantage over current-driven switching in terms of heat dissipation, isothermal voltage-driven switching has been observed only in a few compounds so far, and only in the vicinity of T_N [34,35,39,41,42].

In this proof-of-concept study, we demonstrate the isothermal switching of $\mathbf{L}$ driven by electric fields deep

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in the AFM state of insulating Co_3O_4 . This compound is a spinel, where Co^{2+} ions on the diamond sublattice have spins $S = 3/2$, while Co^{3+} ions on the pyrochlore sublattice are nonmagnetic [43–45]. While Co_3O_4 is centrosymmetric ($Fd\bar{3}m$) in the paramagnetic state, the Co^{2+} ions have no inversion symmetry (site symmetry $\bar{4}3m$) [46] and the onset of Néel-type AFM order at $T_N = 30$ K breaks the global inversion symmetry of the lattice. Correspondingly, Co_3O_4 is a noncentrosymmetric antiferromagnet with a textbooklike collinear AFM state [43,46]. However, the direction of the magnetic easy axis, which can be either along $\langle 111 \rangle$ -type body diagonals or along $\langle 001 \rangle$ -type main cubic axes, has not been resolved yet due to the scarcity of single crystals.

Co_3O_4 and related compounds have been recently reported to exhibit a linear ME effect [46–49] with the following form of the ME free energy [47]:

$$F_{\text{ME}} = -L_x(M_y P_z + M_z P_y) - L_y(M_z P_x + M_x P_z) - L_z(M_x P_y + M_y P_x). \quad (1)$$

Here, x , y , and z axes are main cubic axes, whereas M , L , and P stand for magnetization, AFM Néel vector, and electric polarization, respectively. For weak magnetic fields, when $M \ll L$, Eq. (1) yields a symmetric off-diagonal linear ME susceptibility tensor ($\hat{\alpha}$) in the cubic setting with three independent elements determined by components of the Néel vector: $\alpha_{xy} \propto L_z$, $\alpha_{xz} \propto L_y$, and $\alpha_{yz} \propto L_x$. This specific form, the strength of the ME coupling, and the weak magnetic anisotropy make Co_3O_4 an ideal benchmarking material for the electrical control of $\mathbf{L}$. For instance, the application of an electric field along one of the main cubic axes together with a magnetic field arbitrarily oriented in the plane perpendicular to it should lead to the formation of an AFM monodomain state with $\mathbf{L}$ perpendicular to both fields.

In this Letter, we demonstrate the full control over the orientation of $\mathbf{L}$, achieved by simultaneous electric and magnetic fields in Co_3O_4 . The electrical switching of $\mathbf{L}$ in macroscopic volumes is accomplished only within a few tens of nanoseconds, implying an ultrafast intrinsic switching mechanism for microscopic AFM domains.

AFM domain selection via ME effect—Figure 1 summarizes our results on the linear ME effect in single crystals of Co_3O_4 , grown by chemical transport reaction (see Appendix A). Electric polarization was obtained from conventional pyroelectric or ME current measurements (Appendix B), after poling the crystal with orthogonal electric and magnetic fields, namely $E_p \parallel z$ axis and $H_p \parallel x$ axis, as schematically shown in Fig. 1(d). As clear from Fig. 1(a), the electric polarization emerges below T_N in proportion to the magnetic field, that is characteristic to the linear ME effect. The value of α is found to be as large as

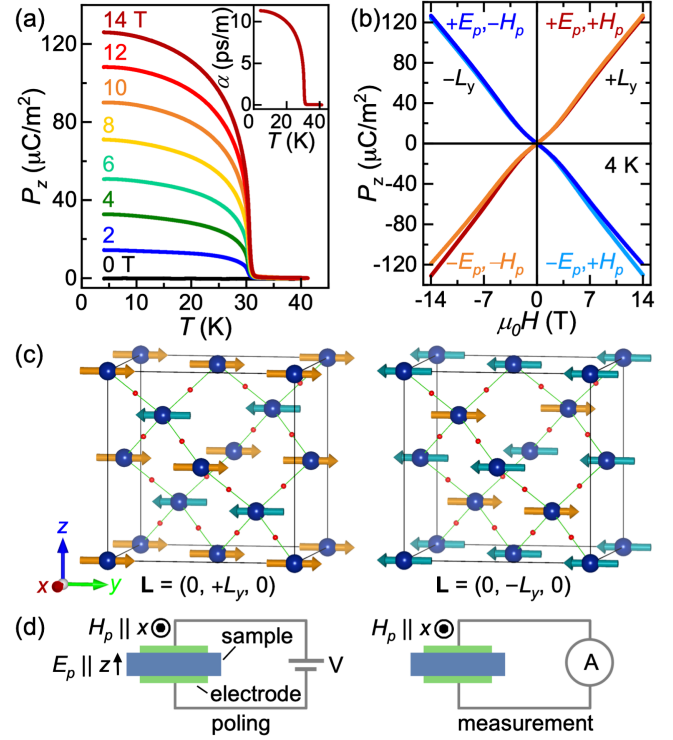


FIG. 1. (a) Temperature-dependent electric polarization P_z measured after ME poling with $E_p = +4.2$ kV/cm ($\parallel z$ axis) and various $\mu_0 H_p$ ($\parallel x$ axis). Inset shows the temperature-dependent ME coefficient α . (b) Magnetic field-dependent P_z at 4 K measured after poling with all four sign combinations of poling fields: $E_p = \pm 4.2$ kV/cm and $\mu_0 H_p = \pm 14$ T. In both cases, P_z was measured with E_p being switched off after poling. (c) Schematics of $+L_y$ and $-L_y$ AFM domain states in Co_3O_4 . Red dots between the Co^{2+} ions of opposite spins indicate the inversion centers in the paramagnetic cubic state, which are broken by the AFM order. (d) Schematics showing the poling procedure and the measurement configuration.

~ 11.3 ps/m at 4 K [inset of Fig. 1(a)], which is 4 times larger than that of the prototypical ME material Cr_2O_3 [34]. Note that α stands for the α_{xz} throughout this Letter. The linear dependence of the electric polarization on the magnetic field in Fig. 1(b) directly evidences the linear ME effect. The sign of α , that is the sign of the slope of the P - H curve, depends on the relative signs of poling fields: α is positive (negative) when the product $H_p E_p$ is positive (negative). These results, together with the presence (absence) of polarization for perpendicular (parallel) orientation of the electric and magnetic fields [shown in Fig. 2(b) and discussed below], confirm the specific form of the linear ME effect in Eq. (1).

For electric and magnetic fields, respectively, applied along the z and the x axes, the ME free-energy term has the simple form $-L_y M_x P_z$ and, thus, the $+L_y$ AFM monodomain state is expected to emerge for $H_p E_p > 0$ and the $-L_y$ monodomain state for $H_p E_p < 0$ [see Fig. 1(c)]. Indeed, such selection of the $\pm L_y$ monodomain states

for opposite signs of $H_p E_p$ is confirmed by the P - H curves in Fig. 1(b). Note that $\pm L_y$ AFM states are interchanged not only by time reversal but also by spatial inversion; that is why the sign of $\mathbf{L}$ is linked to the sign of $H_p E_p$. Before measuring the field-dependent polarization at $T = 4$ K [Fig. 1(b)], the poling electric field was switched off. Since the P - H curve is nearly linear in whole magnetic field range, we conclude that the AFM monodomain state, established by poling with crossed E_p and H_p , was preserved upon the entire magnetic field sweep.

Magnetic anisotropy with easy axes along the cubic $\langle 111 \rangle$ -type directions could prevent the formation of the $\pm L_y$ AFM monodomain states. However, the magnetization of Co_3O_4 is found to be independent of the orientation of the magnetic field (see Fig. S1 in Supplemental Material [50]). The unusual weakness of magnetic anisotropy in Co_3O_4 is crucial for the efficient control of the orientation of $\mathbf{L}$ via the linear ME effect.

In situ magnetic switching of $\mathbf{L}$ —Next, we demonstrate that the AFM monodomain state can be achieved not only by ME poling but can also be created *in situ* (isothermally) from a multidomain state by orthogonal electric and magnetic fields, even at temperatures well below T_N . As a key result, we also show the isothermal control of $\mathbf{L}$ in two ways: its reversal via reversing either electric or magnetic field and its rotation by rotating magnetic field, while keeping a fixed electric field.

For these studies, the sample was cooled to 4 K without any poling fields. In the absence of an electric field, no magnetically induced polarization was observed, indicating the presence of a multidomain state, where $\mathbf{L}$ averages to zero over the sample. When starting from this virgin multidomain state and applying a constant electric field of $E = +17.4$ kV/cm along the z axis, the sample is set to the $+L_y$ monodomain state by magnetic fields exceeding 2–3 T, applied along the x axis. This is shown in Fig. 2(a), where the initial parabolic increase of the P - H curve, indicating the gradual formation of the $+L_y$ monodomain state, turns to linear above this field range, implying no further changes in domain population. Indeed, in +14 T the electric polarization reaches the same value as recorded after ME poling [cf. Figs. 1(a) and 1(b)], also evidencing the formation of the $+L_y$ monodomain state. Intriguingly, when sweeping the magnetic field back with keeping the constant electric field on, the slope of the P - H curve changes sign for negative magnetic fields, indicating the switching from the $+L_y$ to the $-L_y$ monodomain state. This isothermal domain switching process is opposite to the case with no electric field applied, when the poled $+L_y$ monodomain state is preserved upon the sweeping and the sign change of the magnetic field [Fig. 1(b)]. Electric fields as low as +1.7 kV/cm can still induce a majority population of the $+L_y$ ($-L_y$) state in positive (negative) magnetic fields, but the corresponding monodomain states are only

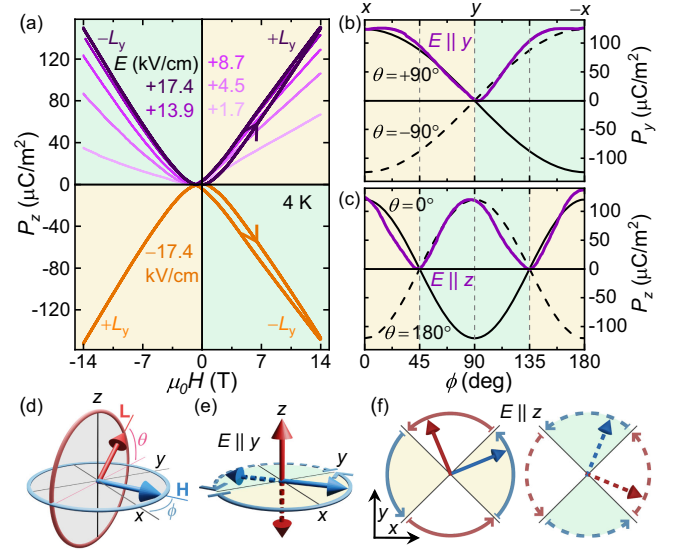


FIG. 2. (a) Magnetic field ($\mathbf{H} \parallel x$) dependence of polarization P_z at 4 K in various electric fields ($\mathbf{E} \parallel z$). (b), (c) Dependence of polarizations P_y and P_z on the orientation of $\mathbf{H}$ (14 T) rotated in the xy plane at 4 K in $\mathbf{E}$ (+17.4 kV/cm) applied along y and z axes, respectively. Purple curves in these panels are the experimental data. Solid (dashed) black curve in (b) indicates P_y (in arb. units) calculated according to Eq. (2) for the $+L_z$ ($-L_z$) monodomain state. Solid (dashed) black curve in (c) shows P_z calculated according to Eq. (3), when $\mathbf{L}$ rotates with preceding (following) $\mathbf{H}$ within xy plane. (d) Sketch showing orthogonality of $\mathbf{L}$ (red arrow) to $\mathbf{H}$ (blue arrow) and introducing the angles ϕ and θ . (e) Sketch showing the favored direction of $\mathbf{L}$, either $+L_z$ or $-L_z$, depending on the orientation of $\mathbf{H}$ rotated within xy plane in $\mathbf{E} \parallel y$. (f) Schematics of in-plane rotation of $\mathbf{L}$ with either preceding (yellow quadrants) or following (green quadrants) $\mathbf{H}$ rotating in xy plane in $\mathbf{E} \parallel z$. In all panels, yellow and green shadings indicate field or angular regions, where $\mathbf{L}$ is preserved [(a), (b), (e)] or continuously rotated [(c), (f)]. At the borders of these regions $\mathbf{L}$ changes sign.

reached for $E \geq +8.7$ kV/cm, as seen in Fig. 2(a). The domain selection and switching processes are also demonstrated in Fig. 2(a) for the opposite sign of the electric field.

Pulsed voltage control of AFM domains—This section describes our key result, that is, the isothermal switching of $\mathbf{L}$ by pulsed electric fields. Figure 3(a) displays the effect of $+, +, -, -, \dots$ voltage pulse sequences on an initially multidomain crystal at 4 K. The rise time of the pulses applied along the z axis was $t_r = 0.3$ s and the sample was exposed to a static magnetic field parallel to the x axis. The measured current exhibits peaks only when the sign of the voltage pulse is changed, i.e., at the first $+$ and first $-$ pulses. These current peaks originate from the electric field-induced switching of ME polarization, i.e., the formation of $+L_y$ monodomain state and its switching to the $-L_y$ state. The lack of current peaks associated with the second $+$ and the second $-$ pulses indicates that the first $+$ and $-$ pulses established the $+L_y$ and $-L_y$ monodomain

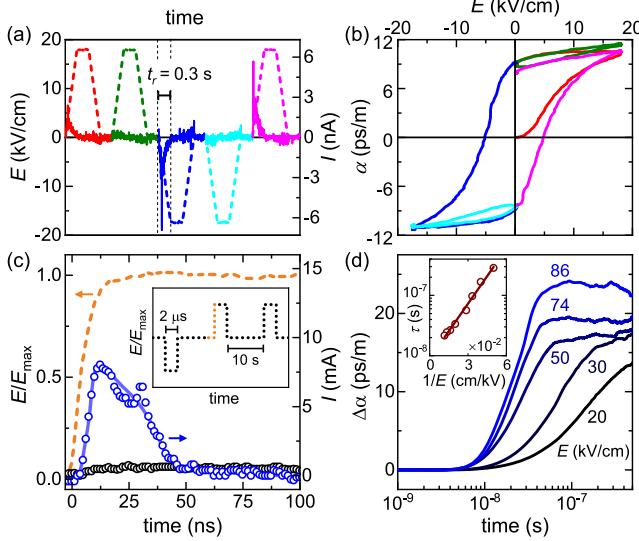


FIG. 3. (a) The +, +, -, -, ... electric pulse sequence (dashed line, left-hand scale) for $E_{\parallel z}$ and the measured switching current (solid line, right-hand scale) at 4 K in +14 T ($\parallel x$). (b) ME hysteresis loop at 4 K in +14 T. The coloring of segments is according to (a). (c) Rising edge of the electric pulse (left-hand scale) with a nominal rise time of $t_r \sim 10$ ns and time traces of switching current (right-hand scale) measured with pulse strengths of +20 kV/cm (black circles) and +86 kV/cm (blue circles) in +14 T at 4 K. Complete sequence of pulses is shown in the inset. (d) Temporal evolution of the change in α , denoted by $\Delta\alpha$, for pulses with a rise time of ~ 10 ns and various strengths. Inset shows the time τ required to reach 50% of maximum value of $\Delta\alpha$ versus the inverse of pulse strength. Solid line in inset is a fit with Merz's law.

states, respectively. During the switching process, the time dependence of α is obtained by dividing the polarization (the time integral of the current) by the magnetic field value. The switching process is more easily accessible in Fig. 3(b), where we directly plot α versus electric field, which resembles a typical ferroelectric hysteresis loop, and demonstrates that α , and thus $\mathbf{L}$, is reversed when the electric field is inverted (Fig. S2 in Supplemental Material shows a similar ME hysteresis loop observed on micrometer scale of the sample, recorded via magnetoelectric force microscopy [50]). Note that both the formation of the $+L_y$ AFM monodomain state from the initial multidomain state by the first + pulse (red curve) and its switching by the first - pulse (blue curve) occur in a nonvolatile manner, as indicated by the high-remanent values of α observed after these pulses in Fig. 3(b). We also determine the threshold electric and magnetic fields required to create an AFM monodomain state isothermally, and show that $\mathbf{L}$ can be switched reversibly and repetitively by subsequent voltage pulses (see Supplemental Material Note 3 for details [50]).

Next, we investigate the dynamics of AFM domain switching with particular interest on the switching speed, a parameter highly relevant to device applications. In these

experiments, we applied a sequence of -, +, + voltage pulses with rise times of approximately 10 ns and also recorded the switching current in real time. These experiments have the same basic concept as the previous ones performed with a much longer rise time of the pulse (0.3 s), but they require a more advanced electronics (see Appendix C) [59,60]. The driving scheme is illustrated in the inset of Fig. 3(c), while the orange curve in Fig. 3(c) shows the initial part of the first + pulse. The initial - pulse is expected to turn the virgin multidomain state to the $-L_y$ domain state, which is then switched to the $+L_y$ state by the first + pulse. The current recorded during the first + pulse contains both the switching current as well as the capacitive current response. If the switching is nonvolatile, the second + pulse should contain only the capacitive response. Thus, subtracting the current traces after the two pulses provides the nonvolatile part of the response, i.e., the current due to the nonvolatile switching of α . The blue curve in Fig. 3(c) displays this nonvolatile switching current achieved with a pulse strength of $E = +86$ kV/cm. It clearly shows that the switching is initiated almost instantaneously, as indicated by the sudden rise in the switching current on the 10 ns scale. The switching is fully completed within less than ~ 50 ns. For comparison, we also show in Fig. 3(c) (black curve) that the switching current is almost negligible for pulses with a smaller amplitude of $E = +20$ kV/cm. The temporal evolution of the change in α , denoted as $\Delta\alpha$, is shown in Fig. 3(d) for various strengths of the pulses. We found that decreasing the pulse strength increases the switching time, which is in accordance with Merz's law: $\tau(E) = \tau_0 e^{E_0/E}$, where τ and τ_0 represent the switching times at a finite E and in the limit of $E \rightarrow \infty$, respectively, and E_0 is the activation electric field [61–63]. The inset of Fig. 3(d) displays the time required to reach 50% of the maximum of $\Delta\alpha$ (halfway switching) versus the inverse of the electric field strength of the pulses. This follows Merz's law, implying that the intrinsic switching time in Co_3O_4 is further reduced if the pulse strength is further increased.

We also note that the switching time of a few tens of nanoseconds is observed in a macroscopic sample volume; hence a faster switching is expected upon reducing the volume where the switching is triggered, as described in the following. The sound velocity associated with the AFM magnon band in Co_3O_4 is $v_m = 2.3$ km/s [64], which imposes a fundamental limit for the speed of the AFM domain walls. This maximum domain wall speed leads to a switching time of the order of 40 ns for the 0.1 mm thick sample studied here, which is close to the value we observed for electric pulses of the highest strength. Importantly, a switching time of $\tau \simeq 100$ ps is expected for switching $\mathbf{L}$ in volumes of 200 nm lateral size in Co_3O_4 , which is 3 orders of magnitude faster than $\tau = 100$ ns observed for a heterostructure based on 200 nm thick Cr_2O_3 films [65]. Whether this fundamental speed limit can be reached by AFM domain walls in Co_3O_4 requires

additional studies, investigating the switching dynamics on the subnanosecond timescale.

Kinetics of $\mathbf{L}$ —After demonstrating the isothermal magnetic and electric switching of $\mathbf{L}$, we trace the field-driven motion of $\mathbf{L}$ by measuring the corresponding variation of the electric polarization and analyzing it using Eq. (1). Because of the negligibly small anisotropy, the Zeeman energy is the dominant term in fields above 2 T and the induced magnetization $\mathbf{M}$ is parallel to the field. Thus, $\mathbf{L}$ becomes confined to the plane perpendicular to the magnetic field but can almost freely rotate therein, as depicted in Fig. 2(d). By also applying an electric field, a unique orientation of $\mathbf{L}$ can be selected, that we probe experimentally via the polarization according to Eq. (1).

Figures 2(b) and 2(c), respectively, show the dependence of P_y and P_z on the orientation of $\mathbf{H}$, rotated in the xy plane. In the two cases, $\mathbf{E}$ was applied along the measured polarization component, i.e., along the y and z axes. Based on Eq. (1) and the orthogonality of $\mathbf{L}$ to $\mathbf{H}$, the angular dependence of two polarization components reads as

$$P_y \propto M_z L_x + M_x L_z = \eta \cos(\phi) \sin(\theta), \quad (2)$$

$$P_z \propto M_x L_y + M_y L_x = \eta \cos(2\phi) \cos(\theta), \quad (3)$$

where η is a constant factor, ϕ is the angle between $\mathbf{H}$ and x axis, and θ is the angle of $\mathbf{L}$ with respect to xy plane, as shown in Fig. 2(d). Since the magnetic anisotropy is negligible, the angle θ is determined by the ME free energy. When $\mathbf{E}$ is applied along the y axis, ME free energy is minimized by the $+L_z$ state ($\theta = +90^\circ$) and the $-L_z$ state ($\theta = -90^\circ$) for $0^\circ < \phi < 90^\circ$ and $90^\circ < \phi < 180^\circ$, respectively, as depicted in Fig. 2(e) (see Supplemental Material Note 4 and Fig. S5 for details [50]). Thus, upon rotation of $\mathbf{H}$, the $+L_z \rightarrow -L_z$ switching is expected when $\mathbf{H}$ and $\mathbf{E}$ become parallel, while the backswitching should take place when they are antiparallel. The solid (dashed) black curve in Fig. 2(b) indicates the behavior of P_y calculated according to Eq. (2), for the $+L_z$ ($-L_z$) monodomain state. The angular dependence of the measured P_y [purple curve in Fig. 2(b)] is well captured by this model, confirming the sudden switching between the $\pm L_z$ states.

When $\mathbf{E}$ is applied along the z axis, by modeling of the polarization data of Fig. 2(c), we find that $\mathbf{L}$ rotates within the xy plane. In one quadrant $\mathbf{L}$ rotates with preceding $\mathbf{H}$, then it suddenly changes sign and follows $\mathbf{H}$ in the next quadrant, as sketched in Fig. 2(f) (for details see Supplemental Material Note 4 and Fig. S6 [50]). These results speak for the full controllability of $\mathbf{L}$ via the ME effect, and no significant influence of magnetic anisotropy on the kinetics of $\mathbf{L}$. Such an unconstrained isothermal ME control of $\mathbf{L}$ even well below T_N makes Co_3O_4 unique among antiferromagnets.

Conclusions—We demonstrated the fast manipulation of AFM states in the isotropic collinear antiferromagnet Co_3O_4 by utilizing its strong linear ME effect. We showed that the AFM Néel vector can be either rotated smoothly or reversed isothermally by electric fields. Furthermore, our results revealed the nanosecond dynamics of the nonvolatile and reversible switching process of macroscopic AFM domains and indicate that the switching process can be even faster for microscopic domains. In this context, studying the switching dynamics in Co_3O_4 thin films and exploring possible optical switching on the subnanosecond scale would be particularly important. Using Co_3O_4 as a template material, the present study represents an important step toward the on-demand electric control of AFM states in insulators. This Letter is expected to stimulate further experimental and theoretical studies, eventually leading to the realization of fast-operation AFM spintronic devices.

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S. G. and M. W. contributed equally to this work.

The authors declare no conflict of interests.

Data availability—The data that support the findings of this Letter are openly available [66].

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End Matter

Appendix A: Single crystal growth—Single crystals of Co_3O_4 were grown by chemical transport reaction method using the preliminary treated high purity powder of Co_3O_4 together with anhydrous TeCl_4 transport agent. The growth was performed in a horizontal two-zone furnace with source temperature of 830°C and a temperature gradient of 40°C to 25°C . After four weeks of transport, octahedral-shaped single crystals were successfully obtained (see Fig. S7 in Supplemental Material [50]). These crystals have as-grown $\{111\}$ -type faces and $\langle 110 \rangle$ -type edges. Figure S7 also includes a Laue pattern on a (001)-cut single crystal and a powder x-ray diffraction pattern on crushed single crystals, confirming the purity of the phase.

Appendix B: Pyroelectric and ME measurements—Crystals with flat (001) surfaces were prepared for the measurements. Contacts on two parallel (001) surfaces were made by silver paint. All measurements were carried out in an Oxford helium-flow cryostat, where the electrical measurements were performed up to the lowest temperature of 4 K and the highest magnetic field of 14 T. Temperature- and magnetic field-dependent electric polarization were obtained via the pyroelectric and ME current measurements, respectively, with a Keysight electrometer (B2987A). For angular-dependent electric polarization study, the ME current was recorded under a rotating magnetic field of 14 T at a constant electric field of $+17.4 \text{ kV/cm}$ by using a home-designed probe, where the sample platform can be rotated by a stepper motor. For the data shown in Fig. 1, the sample was cooled with E_p and H_p from 45 K to 4 K and the pyroelectric or ME current was measured after switching off the electric field. For the data shown in Figs. 2 and 3, the measurements were performed on a virgin

multidomain sample without any ME cooling. In all these cases, the electric polarization was obtained by performing integration of the measured pyroelectric or ME current over time.

Appendix C: Voltage-pulse-driven switching experiments—For voltage-driven switching of AFM domains, we applied voltage pulses ($\parallel z$) in $+14 \text{ T}$ ($\parallel x$) at 4 K in (001)-cut crystal. Time traces of current were simultaneously recorded, from which we determined the polarization and α . For data shown in Figs. 3(a) and 3(b), we used a AixACCT TF Analyzer 2000, equipped with high voltage booster HVB 1000 and Krohn-Hite model 7500 amplifier, which allowed the switching measurements in voltage pulses of rise times down to a few microseconds. The measurements were performed on a sample with a thickness of 0.25 mm. To obtain the purely ME contribution, we subtracted the current arising from the capacitive response in zero magnetic field from the current measured in applied magnetic fields. For switching time determination, a different experimental setup was implemented, as schematically shown in Fig. S8 in Supplemental Material [50]; see also [59,60]. This setup enabled the current measurements directly down to nanosecond timescale in applying voltage pulses of rise times $\sim 10 \text{ ns}$. In these measurement schemes, a positive voltage pulse with a rise time of $\sim 10 \text{ ns}$ was applied to a 0.1 mm thick sample, in which an initial $-L_y$ domain state was already prepared by the same pulse of opposite polarity in $+14 \text{ T}$ at 4 K. The corresponding switching current was measured under various strengths of the pulses. The capacitive response was eliminated by measuring current in applying the identical positive pulses immediately after each switching event.