The single-atom bit represents the ultimate limit of the classical approach to high-density magnetic storage media. So far, the smallest individually addressable bistable magnetic bits have consisted of 3–12 atoms4–12. Long magnetic relaxation times have been demonstrated for single lanthanide atoms in molecular magnets4–12, for lanthanides diluted in bulk crystals13, and recently for ensembles of holmium (Ho) atoms supported on magnesium oxide (MgO)14. These experiments suggest a path towards data storage at the atomic limit, but the way in which individual magnetic centres are accessed remains unclear. Here we demonstrate the reading and writing of the magnetism of individual Ho atoms on MgO, and show that they independently retain their magnetic information over many hours. We read the Ho states using tunnel magnetoresistance15,16 and write the states with current pulses using a scanning tunnelling microscope. The magnetic origin of the long-lived states is confirmed by single-atom electron spin resonance17 on a nearby iron sensor atom, which also shows that Ho has a large out-of-plane moment of 10.1 ± 0.1 Bohr magnetons on this surface. To demonstrate independent reading and writing, we built an atomic-scale structure with two Ho bits, to which we write the four possible states and which we read out both magnetoresistively and remotely by electron spin resonance. The high magnetic stability combined with electrical reading and writing shows that single-atom magnetic memory is indeed possible.

The demonstration of magnetic bistability in single-molecule magnets containing one rare-earth atom6,9,11 illustrated the potential of single-atom spin centres in future storage media5,7,8,10,12. A ligand field that provides a barrier against magnetization reversal by lifting the Hund degeneracies in single-molecule magnets4–11 can also be realized for atoms bound to a surface16–21. While a break junction probes the quantum states of one isolated molecule22, a surface enables preparation of and access to numerous spin centres. Magnetic lifetimes in the range of milliseconds were accordingly obtained for single 3d atoms on MgO (ref. 23), but a recent report of magnetic bistability for Ho atoms on a platinum surface is debated24–26. A major advance of observing magnetic remanence was recently achieved with an ensemble of isolated Ho atoms on MgO (ref. 14), yet the question remained whether electrical probing of the highly localized orbitals of individual rare-earth atoms is possible27,28.

Here we address the magnetic bistability of individual Ho atoms on MgO, which we switch using current pulses and detect through the tunnel magnetoresistance using a spin-polarized scanning tunnelling microscope (STM)15. We unambiguously prove the magnetic origin of the switching in the tunnelling resistance using STM-enabled single-atom electron spin resonance (ESR) on an adjacent iron (Fe) sensor atom. Additionally, we determine by this method the out-of-plane component of the Ho magnetic moment, and use the long lifetime to store two bits of information in an array of two Ho atoms.

![Image](https://example.com/image.png)

Figure 1 | Experimental set-up and magnetic switching of holmium. a, Topographic image of a Ho and an Fe atom on bilayer MgO. The magnetic states of Ho are controlled and probed with an STM using spin-polarized tunnelling ($V = 10 \text{ mV}, I = 10 \text{ pA}$). b, The magnetoresistive tunnel current $I$ recorded atop a Ho atom (STM image in a) shows switching between two magnetic states (red, down; blue, up) of long residence time ($V = 150 \text{ mV}$, current set point $I = 25 \text{ pA}$). At these tunnelling conditions, switching is induced by tunnelling electrons. c, The switching rate $\Gamma$ at $B_z \approx 50 \text{ mT}$ scales as $\Gamma = a(U_{\text{L}0})^b$, where $N$ is close to unity and $a$ is a switching coefficient (see Methods, $V = 150 \text{ mV}, I_0 = 1 \text{ pA}$). d, The voltage dependence at $B_z \approx 50 \text{ mT}$ of $\Gamma$ at constant current ($I = 1.5 \text{ nA}$) reveals three rate-increasing thresholds at $V_1 = 73 \pm 1 \text{ mV}$, $V_2 = 104 \pm 1 \text{ mV}$ and $V_3 = 119 \pm 1 \text{ mV}$. The solid line is a three-segment piecewise linear fit. The uncertainty of the fits in $c$ and $d$ indicate the standard deviation on the least-squares fit parameter.
whose magnetic state can be read locally by magnetoresistance, and remotely by means of ESR on a nearby sensor atom.

Figure 1 shows our experimental set-up consisting of a low-temperature STM with ESR capability, which uses an Fe atom as a local magnetometer to determine nearby magnetic moments. A total magnetic field $B = 0.495$–$0.9$ T is applied nearly in-plane, yielding an out-of-plane component $B_z \approx 50$–$100$ mT that sets the Zeeman splitting of the Fe field sensor. Upon dosing Ho on bilayer MgO, we find individually adsorbed Ho atoms in two binding sites: atop oxygen and on bridge sites, in agreement with previous reports. Here we focus on Ho atoms atop oxygen—the Ho species that shows long lifetime and note that we can move individual Ho atoms from bridge to oxygen sites by using the STM tip and by applying voltage pulses. The co-adsorbed Fe sensor atoms can be distinguished from Ho by a lower topographic height and by their spectroscopic fingerprint: Fe atoms show inelastic spin excitations at approximately 14 meV (ref. [21]); Ho atoms are devoid of spin-excitation signatures. However, we measure a two-state signal on Ho atoms that shows discrete changes in conductance of typically 2%–4% with a spin-polarized tip (Fig. 1b). The current trace has plateaus of long residence times in the high- and low-conductance states. For the sample bias voltage $V = 150$ mV used in Fig. 1c, the magnetic residence time ranges from dozens of seconds to fractions of a second for tunnel currents $I = 6$–$600$ pA. The essentially linear increase in the switching rate (Methods) with tunnel current indicates a single-electron rate-limiting process with a miniscule switching probability of the order of $10^{-9}$ per tunnelling electron (see also Extended Data Fig. 1). We observe that the Ho states remain stable for hours when the bias voltage is kept below $V \approx 73$ mV (Extended Data Fig. 1). At higher voltages we see an increasing switching rate of the Ho states with bias voltage (Fig. 1d). We therefore have two means to control the switching rate: the tunnel current and the bias voltage. To write the Ho state, we repeatedly subject the Ho atom to a current pulse at $V > 150$ mV, until we detect a change in magnetoresistance at $V = 50$ mV that indicates that the Ho atom is in the desired final state. Three rate-increasing voltage thresholds appear in Fig. 1d and Extended Data Fig. 1, which may reflect transition energies between different magnetic states of Ho on MgO.

In the following, we use a nearby Fe sensor atom to prove that the two Ho states correspond to two magnetic orientations of the Ho moment. The Fe sensor acts as a local magnetometer because the Zeeman splitting of its ground states responds to the dipolar field of the nearby Ho atom. The Zeeman splitting of the Fe sensor, which is dominated by the external out-of-plane magnetic field $B_z$, is therefore shifted to lower frequency when the Ho moment is aligned in the direction of $B_z$, and to higher frequency when it is aligned in the direction of $-B_z$. The ESR spectrum on the Fe sensor in Fig. 2a reveals a single resonance peak when Ho was in its high-conductance state. After switching Ho to the low-conductance state, the ESR peak correspondingly shifted to lower frequency. We find that the frequency difference $\Delta f$ sensitively depends on the Fe–Ho distance, as seen in Fig. 2b. The identical scaling for different Fe–Ho pairs shows the equivalent magnetic structure among distinct Ho atoms. Following previous work, we describe the $\Delta f$ versus distance scaling in terms of the magnetic dipole–dipole interaction for out-of-plane polarized moments. Using the Fe moment of $(5.44 \pm 0.03)\mu_B$ (where $\mu_B$ is the Bohr magneton and the error given here and elsewhere represents the standard deviation in the fit parameter) on the same MgO/Ag(100) surface, a one-parameter fit yields the Ho moment of $(10.1 \pm 0.1)\mu_B$. A magnetic moment of $10.1 \mu_B$ suggests a $4f^{10}$ Ho(III) ion configuration where its total angular momentum $J$ is polarized out-of-plane ($J_z = \pm 8$). Note that we are sensing the out-of-plane component of the total magnetic moment, which includes contributions from all orbitals in addition to the dominant $4f$ electrons (see Methods). The previously deduced lower $J_z$ value could be influenced by the averaging over Ho atoms in different adsorption sites on MgO in the X-ray ensemble measurements (see Methods).
Most importantly, however, the correlation of Ho in high- and low-conductance states to the respective ESR frequencies unambiguously proves the magnetic origin of the two-state switching for Ho. In addition, the presence of only one ESR peak in each spectrum acquired over many minutes is a consequence of the extraordinary stability of the magnetic state of the Ho atom.

The high stability of the Ho moment could find use in single-atom data storage applications. To exemplify this point, we built a stable two-bit atomic Ho array (Fig. 3a) and measured the Ho states non-invasively using ESR on a nearby Fe sensor (Fig. 3b). The frequency differences between the four ESR lines were engineered with the knowledge of our dipole–dipole interaction in Fig. 2b in mind. Accordingly, after setting the Ho bits individually to their up and down states, we observe one of four distinct ESR lines on the Fe sensor, identifying the four possible states of the Ho bit array. During the 5 h of deliberately reading and writing the magnetic states of the atoms at 1.2 K, we did not observe unintended magnetic switching of the neighbouring atom. Similarly, monitoring the ESR frequency at 4.3 K confirmed the stability of the Ho states at higher temperature (Extended Data Fig. 2).

The use of single-atom magnets as building blocks in complex structures should enable future studies of magnetic interactions ranging from pairwise coupling to collective behaviour emerging from dense magnetic arrays, such as in geometrically frustrated systems.30

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to Methods, along with any additional Extended Data display items and Online Content

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Author Contributions F.D.N. conceived the experiment and wrote the manuscript. F.D.N., K.Y., W.P. and P.W. analysed the data. W.P. conceived the atom-switching routine. C.P.L. and A.J.H. enabled and supervised the project. F.D.N., K.Y., W.P. and P.W. analysed the data. W.P. conceived the experiment and wrote the manuscript. F.D.N., K.Y., W.P. and P.W. analysed the data. P.W. conceived the atom-switching routine. C.P.L. and A.J.H. enabled and supervised the project. All authors carried out measurements, discussed the results and contributed to the manuscript.

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The Ho switching rate was measured for negative and positive bias voltages at a total field $B = 0.495\, \text{T}$ and current of $1.5\, \text{nA}$ (Extended Data Fig. 1a). We find the same three rate-increasing voltage thresholds presented in Fig. 1d for negative polarity. From a piecewise linear fit of the form $I' = \sum_{i=1}^{3} c_i V_i$, where $V_i$ between $\pm 70\, \text{mV}$ and $\pm 150\, \text{mV}$, we obtain the threshold values and coefficients displayed in Extended Data Fig. 1c. The Ho switching rate shown in Fig. 1c, d and Extended Data Fig. 1 accounts for the total number of switches—from the up to the down state and vice versa. Because the switching rate becomes too rapid at higher bias values, we obtain a further measure of the fast switching rate by reduced-duty-cycle switching, following the method described ref. 1. With this technique, we subject the atom to a low-duty-cycle train of high-voltage pulses ($0.1\, \text{ms}$ pulse every $0.5\, \text{ms}$) and probe whether the atom has reversed its magnetization using a sub-switching-threshold voltage for read-out. For all switching measurements, the field is applied mostly in-plane with an out-of-plane component of $B_\perp \approx 50\, \text{mT}$ at a total field of $0.495\, \text{T}$. No further voltage thresholds appear up to the maximum voltages probed, $\pm 300\, \text{mV}$, and the switching rate effectively levelled off to approach a constant probability of switching of about $10^{-3}$ per tunnelling electron, independent of the voltage. This suggests that the tunnelling electrons assist reversal of the magnetic state primarily via the $119\, \text{mV}$ transition.

The tunnelling-current-dependent switching rate was measured at different magnetic fields and bias voltages (Extended Data Fig. 1b). The switching rate follows a power law, $I' = a I^b$, in all cases, with an exponent $N$ close to unity, similar to what is shown in Fig. 1c. The fit parameters are $a = (3.5 \pm 2) \times 10^{-3}$ and $N = -0.8 \pm 0.1$ at $120\, \text{mV}$ and $0.9\, \text{T}$; $a = (4 \pm 2) \times 10^{-2}$ and $N = -0.9 \pm 0.1$ at $150\, \text{mV}$ and $0.9\, \text{T}$; and $a = (1.5 \pm 0.1) \times 10^{-2}$ and $N = 0.95 \pm 0.01$ at $150\, \text{mV}$ and $0.495\, \text{T}$. The uncertainties represent the standard deviation in the fit parameter. The switching rates at $0.495\, \text{T}$ ($B_\perp \approx 50\, \text{mT}$) and $0.9\, \text{T}$ ($B_\perp \approx 100\, \text{mT}$) are comparable, but slightly higher at the larger field. A polynomial background was subtracted from the current trace in Fig. 1b to correct for a tip drift of approximately $10\, \text{pm}$. We did not measure switching rates at even smaller fields because a certain magnetic field is required to magnetically polarize the tip, which we need to obtain spin-polarized tunnel currents.
Extended Data Figure 1 | Switching-rate dependence of Ho atoms on MgO/Ag(100). a, Switching rate at a constant current of 1.5 nA and a total field of 0.495 T ($B_z \approx 50$ mT). The three threshold values (listed in c) are identical for positive and negative bias. The light blue circles represent the switching rate that was directly measured from current traces and the dark blue squares show a reduced-duty-cycle measurement for higher switching rates. The black line stems from a piecewise linear fit. b, The current-dependent switching rates follow a power law that has an exponent close to unity for all field and bias conditions. This scaling behaviour indicates a single-electron rate-limiting process in the reversal of the Ho moment by energetic electrons. c, Fit parameters for the switching rate in a. The uncertainties represent the standard deviation in the fit value.

|   | -V        | +V        |
|---|-----------|-----------|
| $V_1$ (mV) | $-73.0 \pm 1.3$ | $73.0 \pm 0.1$ |
| $V_2$ (mV) | $-104.6 \pm 0.3$ | $104.1 \pm 0.1$ |
| $V_3$ (mV) | $-118.6 \pm 0.6$ | $119.2 \pm 0.3$ |
| $c_0$ (s$^{-1}$) | $0.12 \pm 0.02$ | $0.21 \pm 0.01$ |
| $c_2$ (s$^{-1}$) | $4.2 \pm 0.5$ | $13.9 \pm 0.5$ |
| $c_3$ (s$^{-1}$) | $58 \pm 7$ | $89 \pm 3$ |
Extended Data Figure 2 | Temporal stability of a Ho bit at 4.3 K measured with STM-ESR. a, ESR spectra for up (top, red) and down (bottom, blue) alignment of the Ho bit at 4.3 K. The sweeps were normalized to the ESR peak height and vertically offset for clarity.
b, Monitoring the ESR signal at the two frequencies corresponding to up (blue) and down (orange) alignment of the Ho bit (arrows in a) versus time \( t \) \( (V = 60 \text{ mV}, I = 20 \text{ pA}, V_{RF} = 25 \text{ mV}) \). The Ho bit spontaneously switches to the up state at \( t = 1.55 \text{ h} \) and remains in that state for the remainder of the sweep. A polynomial background was subtracted from each trace to correct for lateral tip drift. The gap at \( t = 1.1 \text{ h} \) is an interruption that was used to realign the tip onto the Fe sensor to correct for tip drift.