A classical battery converts chemical energy into a persistent voltage bias that can power electronic circuits. Similarly, a phase battery is a quantum device that provides a persistent phase bias to the wave function of a quantum circuit. It represents a key element for quantum technologies based on phase coherence. Here we demonstrate a phase battery in a hybrid superconducting circuit. It consists of an n-doped InAs nanowire with unpaired-surface states, that is proximitized by Al superconducting leads. We find that the ferromagnetic polarization of the unpaired-surface states is efficiently converted into a persistent phase bias $\varphi_0$ across the wire, leading to the anomalous Josephson effect. We apply an external in-plane magnetic field and, thereby, achieve continuous tuning of $\varphi_0$. Hence, we can charge and discharge the quantum phase battery. The observed symmetries of the anomalous Josephson effect in the vectorial magnetic field are in agreement with our theoretical model. Our results demonstrate how the combined action of spin-orbit coupling and exchange interaction induces a strong coupling between charge, spin and superconducting phase, able to break the phase rigidity of the system.

At the base of phase-coherent superconducting circuits is the Josephson effect: a quantum phenomenon describing the flow of a dissipationless current in weak links between two superconductors. The Josephson current $I_J$ is then intimately connected to the macroscopic phase difference $\varphi$ between the two superconductors via the so-called current–phase relationship (CPR) $I_J(\varphi)$. If either time-reversal ($\mathbb{T} \rightarrow -\mathbb{T}$) or inversion ($\mathbb{I} \rightarrow -\mathbb{I}$) symmetries are preserved, $I_J(\varphi)$ is a function of $\varphi$ and the CPR, in its simplest form, reads $I_J(\varphi) = I_C \sin(\varphi)$ (ref. 4), with $I_C$ being the junction critical current. This means that, as long as one of these symmetries is preserved, an open Josephson junction ($J_J; I_J = 0$) cannot provide a phase bias or, accordingly, a JJ closed on a superconducting circuit ($\varphi = 0$) cannot generate current. As a consequence, the implementation of a phase battery is prevented by these symmetry constraints, which impose a rigidity on the superconducting phase, a universal constraint valid for any quantum phase.

The break of time-reversal symmetry (alone) maintains the phase rigidity but enables two possible phase shifts, $0$ or $\pi$, in the CPR. The $0-\pi$ transition has been extensively studied in superconductor/ferromagnet/superconductor junctions, which has applications in cryogenic memories. On the other hand, if both time-reversal and inversion symmetries are broken, a finite phase shift $0 < \varphi_0 < \pi$ can be induced and the CPR reads as follows:

$$I_J(\varphi) = I_C \sin(\varphi + \varphi_0).$$  

A junction with such CPR, defined as a $\varphi_0$-junction, will generate a constant phase bias $\varphi = -\varphi_0$ in an open circuit configuration, while when inserted into a closed superconducting loop it will induce a current $I = I_C \sin(\varphi_0)$, usually denoted as an anomalous Josephson current. Recently, anomalous Josephson currents have been the subject of theoretical and experimental works envisioning direct applications in superconducting electronics and spintronics.

Lateral hybrid junctions made of materials with a strong spin-orbit interaction or topological insulators are ideal candidates to engineer Josephson $\varphi_0$-junctions. The lateral arrangement breaks the inversion symmetry and provides a natural polar axis perpendicular to the current direction. Moreover, the electron spin polarization induced by either a Zeeman field or the exchange interaction with ordered magnetic impurities breaks the time-reversal symmetry. In this case, the anomalous $\varphi_0$-shifts are ruled by the Lifshitz-type invariant in the free energy ($F_1$), which has the following form:

$$F_1 \approx f(a, h)(n_0 \times \mathbf{\hat{z}}) \cdot \mathbf{v},$$

where $f(a, h)$ is an odd function of the strength of the Rashba coefficient $a$ and the exchange or Zeeman field $h$, $n_0$ is a unit vector pointing in the direction of the latter and $\mathbf{v}$ is the superfluid velocity of the Cooper pairs flowing in the JJ. The scalar triple product then defines the vectorial symmetries of $\varphi_0$, while the amplitude of the shift depends on sample-specific microscopic details as well as macroscopic quantities like temperature.

Driven by the geometric condition for a finite $\varphi_0$-shift (equation (2)), we realized a phase battery (Fig. 1a) consisting of a JJ made of an InAs nanowire (in red) embedded between two Al superconducting poles (in blue). The supercurrent, and hence $\mathbf{v}$, flows along the wire (x direction), which is orthogonal to the effective $SU(2)$ Rashba magnetic field vector pointing out of the substrate plane (z direction) hosting the InAs nanowire ($SU(2)$ stems for the special unitary group of degree 2). In the same nanowire, surface oxides or defects generate unpaired spins behaving like ferromagnetic impurities (represented by yellow arrows in Fig. 1a) that can be polarized along the y direction to provide a persistent exchange interaction $h$.

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in this direction. This leads to a finite triple product in equation (2) and, consequently, to the anomalous $\phi_0$ phase bias.

An Al-based superconducting quantum interference device (SQUID) is used as a phase-sensitive interferometer made with two anomalous $\phi_0$-JJs (in red), as shown in Fig. 1bc (see Supplementary Information for fabrication detail). The device geometry has been conceived to maximize the symmetry of the two JJs (ref. 17) to accumulate the two anomalous $\phi_0$-shifts when applying a uniform in-plane magnetic field. The anomalous phase shift in the SQUID critical current is then given by the following:

$$I_S(\Phi) = 2I_C \cos \left( \pi \frac{\Phi}{\phi_0} + \frac{\Phi_{out}}{2} \right),$$

where $I_C$ is the critical current of each JJ, $\Phi$ is the magnetic flux piercing the ring, $\phi_{out} = 2\phi_0$ is the total anomalous phase shift in the SQUID interference pattern resulting from the $\phi_0$-shifts in each of the JJs (see Section III of the Supplementary Information for details) and $\phi_0 = 2.067 \times 10^{-18}$ Wb is the flux quantum. This model provides a good description of the SQUID interference pattern displayed in Fig. 1c, which shows the voltage drop across the SQUID as a function of the out-of-plane magnetic field $B_z$ and bias current $I$. The red-coloured region of Fig. 1c, corresponding to zero voltage drop, indicates the dissipationless superconducting regime, and the edge of this region provides the $I_C(\Phi)$ dependence. The green line on top of the colour plot is the best fit of $I_C(\Phi)$ from equation (3), with $I_C \approx 300$ nA and no phase shift $\phi_{out} \approx 0$. The latter condition is consistent with the absence of the anomalous phase when the magnetic field has only a component in the $\hat{z}$ direction and the magnetic impurities are not polarized (that is, $\mathbf{n}_B \parallel \hat{z}$ in equation (2)). Notably, there is a replica of the $I_C(\Phi)$ oscillations in the voltage drop $\Delta V(\Phi)$ when $I > I_C$ and the SQUID operates in the dissipative regime (blue region and curve in Fig. 1ce), as conventionally realized with strongly overdamped JJs (ref. 18). This oscillation provides a complementary and fast method to quantify the SQUID phase shifts and is used in the following analysis. Additional measurements on similar devices can be found in Section VI of the Supplementary Information.

The temperature dependence of the device’s normal-state resistance shows an upturn below ~80 K (see Fig. 1d), which is a clear signature of the presence of magnetic impurities that increase, at low temperature, the electron scattering events. The upturn can be additionally realized with strongly overdamped JJs (ref. 18). This oscillation provides a complementary and fast method to quantify the SQUID phase shifts and is used in the following analysis. Additional measurements on similar devices can be found in Section VI of the Supplementary Information.
structure cannot be excluded a priori. Although the amount of intrinsic magnetic impurities is not fully controllable, their presence is crucial for the operation and implementation of the phase battery, as discussed below.

Following the condition imposed by a finite Lifshitz invariant term (equation (2)), we apply an in-plane magnetic field orthogonal to the nanowire axis \( B_y \) to maximize the effect. The \( I_J(\phi) \) dependence then evolves with a clear generation of an anomalous phase shift, as presented in the panels of Fig. 2. The evolution of \( \Delta V(\Phi) \) as a function of \( B_y \) ranging from \(-60\) mT up to \(60\) mT is visible in Fig. 2a and in the selected single traces of Fig. 2b. The resulting phase shift, \( \phi_{\text{tot}} \), exhibits a non-monotonic evolution as a function of \( B_y \), with a maximum shift at \( B_y \approx 5\) mT and a saturation for \(|B_y| \gtrsim 30\) mT (yellow curve in Fig. 2c). When the field is reversed, a hysteretic behaviour is observed (green curve in Fig. 2c), and the evolution of \( \phi_{\text{tot}} \) reverses with a minimum shift at \( B_y \approx -5\) mT. The change of sign of the phase shift agrees with the theoretical prediction of equation (2) when \( h \rightarrow -h \), whereas the observed hysteretic behaviour suggests a ferromagnetic coupling between the magnetic impurities in the nanowire. Trivial hysteretic phase shifts induced by a trapped flux in the superconductor or in the SQUID ring can be excluded (see Section V of the Supplementary Information for more details). At low temperatures, the coexistence of Kondo and ferromagnetism is not unusual and describes well the hysteretic non-monotonic behaviour observed in \( \phi_{\text{tot}}(B_y) \). Indeed, due to the antiferromagnetic nature of the Kondo interaction, the effective exchange field created by these unpaired spins is opposite to the Zeeman field generated by \( B_y \) so that the two contributions are competing in the anomalous phase with a partial cancellation.

This additional component is confirmed by the observation of an intrinsic phase shift, \( \phi_{\text{int}} \), which is present even in the absence of the in-plane magnetic field \( (B_y = 0) \) if a finite \( B_z \) has been previously applied, as shown in Fig. 2d,e. Since it stems from a ferromagnetic ordering, \( \phi_{\text{int}} \) depends only on the history of \( B_z \), and again, the evolution of \( \phi_{\text{int}}(B_z) \) can be extracted and is presented in Fig. 2f. In contrast to the total phase shift, \( \phi_{\text{tot}} \) follows a clear and almost monotonic behaviour that shows a hysteresis in the back and forth sweep direction (blue and red curves of Fig. 2f). The \( \phi_{\text{int}} \) saturates at \(|B_z| \gtrsim 15\) mT in the two asymptotic limits with a total phase drop of \(-\pi\). Furthermore, during the first magnetization of the SQUID, a clear curve resembling the initial magnetization curve of a ferromagnet has been observed (see Supplementary Fig. 2 in the Supplementary Information), confirming the ferromagnetic nature of the impurity ensemble.

We now analyse the extrinsic contribution to the phase shift, \( \phi_{\text{ex}} \), which stems directly from the external \( B \) field. Due to the additive

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**Fig. 2 | Charging loops of the Josephson phase battery.** a. Voltage drop \( \Delta V(\Phi) \) at constant current bias \( I = 1 \mu\text{A} \) versus in-plane magnetic field \( B_y \) applied orthogonal to the nanowire axis. At large \( |B_y| \), the amplitude of \( \Delta V(\Phi) \) is lowered due to the suppression of superconductivity inside the wire. b. Selected traces \( \Delta V(\Phi) \) extracted from a for different \( B_y \). Data are vertically offset for clarity. c. Extracted phase shift \( \phi_{\text{tot}} \) from the curves in a with back (green) and forth (yellow) sweeps in \( B_y \). The shifts are extracted by comparing the single traces to the resistively shunted junction (RSJ) relation \( \Delta V = \frac{\pi}{2} \sqrt{I^2 - 4I^2C} \cos (\pi\Phi/\Phi_0 + \phi_{\text{tot}}/2) \); see the dashed line in b, which serves as an example. d. Colour plot of the persistent voltage drop \( \Delta V(\Phi) \) measured at \( B_z = 0 \) after the magnetic field was swept to the values shown on the y axis. e. Selected traces \( \Delta V(\Phi) \) extracted from d. f. Intrinsic phase shift \( \phi_{\text{int}} \) extracted from d. The \( \phi_{\text{int}} \) stems from the ferromagnetic polarization of the unpaired spins. Error bars in c and f indicate the 1σ standard errors resulting from the fit of the curves in b and e. All data were recorded at 50 mK of bath temperature.
Remarkably, our measurement reveals the odd parity of the anomalous phase, ensuring the complete extraction of the intrinsic contribution. Notice also that the behaviors of $\varphi_{an}$ and $\varphi_{ex}$ in the magnetic field are opposite in sign, as expected from the competition between the exchange interactions induced by the Kondo antiferromagnetic coupling and a Zeeman field, further supporting our assumptions. The dependence $\varphi_{an}(B_x)$ is characterized by a linear increase at low magnetic fields ($|B_x| < 15$ mT) up to a maximum phase shift of $\pm \pi/2$. Remarkably, our measurement reveals the odd parity of the anomalous phase with respect to the magnetic field, one of the main symmetry hallmarks of this effect. This parity is the consequence of the odd parity of the free energy $F_I$ with respect to the exchange field. At higher fields, non-linearities appear, suggesting a non-trivial evolution of $\varphi_{an}$ in the magnetic field. In order to understand this behavior, we have modeled our $\varphi_{an}$-junction set-up by a lateral junction treated within the quasi-classical approach presented in the literature (ref. 2; see Section IV in the Supplementary Information). The resulting $\varphi_{an}$ obtained from the above model is shown in the inset of Fig. 3a. It nicely reproduces the main features of $\varphi_{an}$: the linear dependence at small magnetic fields and the saturation at larger ones. Notice that within the scale of the magnetic field applied in the experiment, the field dependence of the anomalous phase looks as if it saturates at the value close to $\pi/2$. This value is however non-universal and depends on the characteristics of the nanowire. Moreover, if larger values of $B_x$ could be reached, the anomalous phase of each junction would increase up to the universal plateau at $\pi$, as expected also for planar junctions.

At small in-plane fields ($B_{in} = \sqrt{B_x^2 + B_y^2}$) the model leads to a simple expression for the anomalous phase:

$$\varphi_{an} \approx C_1 \alpha^2 B_{in} \sin(\theta) + O(B_{in}^3),$$

where $\theta$ is the angle between the field and the nanowire axis (see Fig. 3b), $C_1$ is a parameter dependent on the temperature and the microscopic details of the JJ and $O$ is the polynomial asymptotic notation. By using typical values of the parameters for the InAs/Al junction, we obtained a $C_1 \approx 0.04 \pi$. mT$^{-1}$, in very good agreement with the experimental data (see Section IV in the Supplementary Information).

The odd symmetry of the anomalous phase dictated by the triple product in equation (2) can be further investigated by measuring $\varphi_{an}$ over all the directions of the in-plane magnetic field. Figure 3c shows the full dependence of $\varphi_{an}$ on the angle $\theta$. As predicted from equation (2), the phase shift is very small for fields along the nanowire axis ($\theta = 0$, green trace in Fig. 3c), showing the maximum slope for the orthogonal magnetic field ($\theta = \pi/2$, blue trace in Fig. 3c). The odd symmetry manifests clearly as well in the slope $\varphi_{an}/\partial \theta$ in the low-field limit (Fig. 3d). The latter is perfectly fitted with a sinusoidal function of $\theta$ in agreement with equation (4) (red trace in Fig. 3d).

In summary, our results demonstrate the implementation of a quantum phase battery. This quantum element, providing a controllable and localized phase bias, can find key applications in different
quantum circuits such as an energy tuner for superconducting flux\textsuperscript{22} and hybrid\textsuperscript{23} qubits, or a persistent multi-valued phase-shifter for superconducting quantum memories\textsuperscript{10,24} as well as superconducting rectifiers\textsuperscript{25}. Moreover, the magnetic control over the superconducting phase opens new avenues for advanced schemes of topological superconducting electronics\textsuperscript{26} based on InAs JJ's\textsuperscript{1,27}. The weak control over the density of unpaired spins makes our proof-of-concept device difficult to reproduce in a massive reliable process. Further technological improvements can be envisioned by a controlled doping of the wires with magnetic impurities\textsuperscript{28} or by the inclusion of a thin epitaxial layer of a ferromagnetic insulator, like EuS\textsuperscript{29}, as recently integrated in similar nanowires\textsuperscript{30}.

**Online content**

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41565-020-0712-7.

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Data availability
The data that support the findings of this study are available from corresponding author E.S. upon reasonable request.

Code availability
The codes that support the findings of this study are available from corresponding author E.S. upon reasonable request.

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Author contributions
E.S., A.I. and O.D. performed the experiment and analysed the data. R.C., C.S.F., C.G., I.V.T., A.B. and F.S.B. provided theoretical support. M.R., N.L. and O.D. fabricated the phase battery on the InAs nanowires grown by V.Z. and L.S.; E.S. conceived the experiment together with F.G., who supervised the project. E.S., A.I., I.V.T. and F.S.B. wrote the manuscript with feedback from all authors.

Competing interests
The authors declare no competing interests.

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