The temperature in the crust of an accreting neutron star, which comprises its outermost kilometre, is set by heating from nuclear reactions at large densities1–4, neutrino cooling5–8 and heat transport from the interior9–11. The heated crust has been thought to affect observable phenomena at shallower depths, such as thermonuclear bursts in the accreted envelope12,13. Here we report that cycles of electron capture and its inverse, β− decay, involving neutron-rich nuclei at a typical depth of about 150 metres, cool the outer neutron star crust by emitting neutrinos and also thermally decoupling the surface layers from the deeper crust. This ‘Urca’ mechanism12 has been studied in the context of white dwarfs13 and type Ia supernovae14,15, but hitherto was not considered in neutron stars, because previous models1,2 computed the crust reactions using a zero-temperature approximation and assumed that only a single nuclear species was present at any given depth. The thermal decoupling means that X-ray bursts and other surface phenomena are largely independent of the strength of deep crustal heating. The unexpectedly short recurrence times, of the order of years, observed for very energetic thermonuclear superbursts16 are therefore not an indicator of a hot crust, but may point instead to an unknown local heating mechanism near the neutron star surface.

Continual accretion onto a neutron star pushes the ashes of surface thermonuclear burning, which is often observed as type I X-ray bursts16,17, to greater pressures and densities, at which the nuclei form a rigid lattice18 known as the crust. With increasing depth, these ashes are transformed by capture of degenerate electrons into increasingly neutron-rich nuclei19. An electron-capture reaction—(Z, A) + e− → (Z − 1, A) + νe—involves a parent nucleus (Z, A) with charge number Z and mass number A and gives rise to a daughter nucleus (Z − 1, A) with the emission of an electron neutrino; this occurs at a well-defined depth, where the electron chemical potential μe ≈ |Q_{EC}| + E_{X}. Here |Q_{EC}| is the (negative) electron-capture Q-value (the difference between the parent and daughter ground-state masses and hence the energy needed for the reaction to occur) and E_{X} is the excitation energy of the lowest state in the daughter nucleus that can be populated by electron capture. In the commonly used zero-temperature approximation, the reverse β−-decay reaction (Z − 1, A) → (Z, A) + e− + νe is blocked because there is no phase space available in which to re-emit the captured electron. At finite temperature and for E_{X} < kT, however, β− decay via the re-emission of an electron with an energy close to |Q_{EC}| is not completely blocked. As a result, the boundary between a layer containing nuclei (Z, A) and a deeper layer containing (Z − 1, A) is a shell with mixed composition spanning a range of electron chemical potential |Q_{EC}| − kT < μe < |Q_{EC}| + kT that corresponds to a thickness of a few metres within the neutron star crust. Inside this shell, both electron capture and its inverse, β− decay, occur (see Fig. 1). If these reactions cycle back-and-forth rapidly, the

Figure 1 | Schematic nuclear energy-level diagrams for an electron-capture/β−-decay pair. a, Illustration of compositional layers in the neutron star crust; b–d, energy level diagrams. In the shallow region above the Urca shell, where the nuclear composition has charge number Z and mass number A, Z, the electron chemical potential μe is less than |Q_{EC}|, the energy threshold for electron capture, and electron capture is energetically blocked (b). In the deeper region below the Urca shell, μe > |Q_{EC}|: electron capture has therefore occurred, the composition consists of nuclei (Z − 1, A), and the degenerate electrons block the phase space for electron emission via β− decay (d). In the Urca shell between these regions, μe = |Q_{EC}|. As a result, both electron capture (EC) and β− decay (β) are possible (c), and rapid cycling between the nuclei (Z, A) and (Z − 1, A) leads to a strong neutrino emissivity.
result is a strong neutrino emission, known as an Urca process, that cools the neutron star crust.

Such Urca shells are thought to also operate in white dwarfs, type Ia supernovae, and stellar ONeMg cores producing electron-capture supernovae. But the effect has not been considered in the context of accreting neutron stars. Most earlier models of accreted crusts were computed in the zero-temperature limit, in which the composition switches sharply at the energetic thresholds with no available phase space for cycling; indeed, in this limit, only one nuclide of a reaction pair is present at a given depth. Urca shell cooling relies on phase space unblocking at finite temperature and the presence of both reaction pair nuclei in the shell. More recent reaction network calculations did not include $\beta^-$-decays as they were not considered to be important, and any Urca cycling was estimated to be negligible. The importance of Urca shell cooling is revealed here through the use of a full reaction network that includes both electron capture and $\beta^-$ decay on an equal footing, that takes into account the rates of subsequent reactions that deplete the electron-capture/$\beta^-$-decay pairs, and that follows the evolution in time of a fluid element as it is pushed through a reaction shell.

In order for this cycling of electron capture and $\beta^-$ decays between two nuclear species to occur, the nuclei involved must satisfy two conditions. First, the transitions must proceed between low-lying states ($E_x \lesssim kT$) for both the electron capture and the $\beta^-$ decay). In addition, within an electron-capture/$\beta^-$-decay pair, the nucleus undergoing $\beta^-$ decay must not have a strong electron-capture branch, as these electron captures would remove nuclei from the Urca cycle, thereby reducing its effect or eliminating it entirely. The cooling rate depends on the strength of the transition (the $\beta^-$ value), which is proportional to the matrix element connecting the parent and daughter states) and the energy threshold; the integration over available phase space produces a characteristic $T$ scaling with temperature. The formation of Urca shells with large cooling rates is enabled by strong nuclear deformations that tend to spread nuclear electron-capture strength to lower

### Table 1 | Electron-capture/$\beta^-$-decay pairs with highest cooling rates

| Electron-capture/$\beta^-$-decay pair | Density $^\dagger$ | Chemical potential $^\ddagger$ | Luminosity $^\S$ |
|--------------------------------------|------------------|-----------------------------|------------------|
| $^{25}$Mg $^{25}$Na $^{59}$Ti $^{59}$Sc $^{31}$Al $^{33}$Mg $^{56}$Ti $^{56}$Sc $^{57}$Cr $^{57}$V $^{57}$Ti $^{57}$Sc $^{63}$Cr $^{63}$V $^{57}$V $^{57}$Ti $^{57}$Sc | $4.79$ | $13.3$ | $24$ |
| $^{59}$Ti $^{59}$Sc $^{55}$Ca | $3.73$ | $12.1$ | $11$ |
| $^{31}$Al $^{33}$Mg | $3.39$ | $11.8$ | $8.8$ |
| $^{33}$Mg | $5.19$ | $13.4$ | $8.3$ |
| $^{56}$Ti $^{56}$Sc | $5.57$ | $13.8$ | $3.5$ |
| $^{57}$Cr | $1.22$ | $8.3$ | $1.6$ |
| $^{63}$V | $2.56$ | $10.7$ | $1.6$ |
| $^{105}$Zr | $6.82$ | $14.7$ | $0.97$ |
| $^{63}$Cr $^{63}$V | $3.12$ | $11.2$ | $0.92$ |
| $^{69}$Mn | $0.945$ | $7.6$ | $0.88$ |
| $^{103}$Sr $^{103}$Rb | $5.30$ | $13.3$ | $0.65$ |
| $^{96}$Kr $^{96}$Br | $6.40$ | $14.3$ | $0.65$ |
| $^{66}$Fe | $2.34$ | $10.3$ | $0.60$ |
| $^{65}$Mn | $3.55$ | $11.7$ | $0.46$ |

$^\dagger$ The listing of two electron-capture daughter isotopes means that two subsequent reaction pairs occur in the same layer.

$^\ddagger$ The transition always occurs at the specified electron chemical potential. The density, which is for a composition consisting of nuclei with a single mass number, $A$, will only be approximate for an arbitrary composition.

$^\S$ The cooling luminosity $L$ scales with temperature $T$, local gravitational acceleration $g$, neutron star radius (in the local rest frame) $R$, and mass fraction $X$ of the respective electron-capture/$\beta^-$-decay pair as $L \propto X R^2 g^{-1}$. The temperature scaling assumes $E_x \propto kT$. For further details, see Supplementary Information section 1. The values for $L$, we quote here for $T = 0.51$ $\text{GK}$, $g = 1.85 \times 10^{14}$ $\text{cm s}^{-2}$, $R = 12$ $\text{km}$ and $X = 1$. The existence of the $^{105}$Zr-$^{105}$Sc electron-capture/$\beta^-$-decay pair depends strongly on nuclear masses. In all other cases nuclear-physics-related uncertainties of the predicted luminosities are of the order of a factor of $3$–$4$ (see Supplementary Information section 5).

**Figure 2** | Electron-capture/$\beta^-$-decay pairs on a chart of the nuclides. The thick blue lines denote electron-capture/$\beta^-$-decay pairs that would generate a strong neutrino luminosity in excess of $5 \times 10^{44}$ $\text{ergs}^{-1}$ at $T = 0.51$ $\text{GK}$ for a composition consisting entirely of the respective electron-capture/$\beta^-$-decay pair. They largely coincide with regions where allowed electron-capture and $\beta^-$-decay transitions are predicted to populate low-lying states and subsequent electron capture is blocked (shaded squares, see also the discussion in ref. 3). These are mostly regions between the closed neutron and proton shells (pairs of horizontal and vertical red lines), where nuclei are significantly deformed (see Supplementary Information section 4). Nuclides that are $\beta^-$-stable under terrestrial conditions are shown as squares bordered by thicker lines. Nuclear charge numbers are indicated in parentheses next to element symbols.
excited states, thereby lowering $E_\nu$, (ref. 21; see Extended Data Fig. 1). There are a number of electron-capture/$\beta^-$decay pairs that fulfill these conditions for forming fast-cooling Urca shells (see Table 1 and Fig. 2). The degree to which these shells are activated in a neutron star crust depends on the initial composition produced by thermonuclear burning on the neutron star surface. Because electron capture in the outer crust preserves the mass number $A$, the abundance of an electron-capture/$\beta^-$decay pair, and therefore its absolute neutrino luminosity, is set by the abundance of nuclei with the same mass number in the ashes of the surface thermonuclear burning. As is evident from Fig. 3, neutrino cooling by Urca shells is by far the dominant neutrino emission process in the crust for typical crust compositions.

The greatly enhanced crust neutrino emissivity at shallow depths changes the long-standing assumption that rapidly accreting neutron stars have a significant luminosity from deep crustal heating, which directly influences thermonuclear burning in their accreted envelopes. In the absence of crust Urca shells, if the crust has a low thermal conductivity, and if the core neutrino emissivity is weak, then deep crustal heating would generate significant heat flow towards the neutron star surface. Models of thermonuclear bursts\textsuperscript{11,17} use this emergent luminosity from the deep crust as a boundary condition, which sets in part the ignition density and temperature. The presence of strongly temperature-sensitive Urca cycles limits the temperature at the location of the shells, however, and may even require an inward directed luminosity from the accreted envelope. Even for conditions in the deep crust that are favourable for sending a large heat flux to the surface, the Urca shells re-emit this heat as neutrinos, thereby preventing it from reaching the surface layers (see Supplementary Information section 3).

To establish the robustness of our conclusions with respect to nuclear physics uncertainties, we used two different mass models, namely FRDM\textsuperscript{23} and HFB-21\textsuperscript{24}. The use of FRDM masses instead of those from HFB-21 reduces the Urca-shell neutrino luminosity by 90% for a superburst ash composition (see Supplementary Information section 5 for details). For both mass models, the temperature at the superburst ignition depth is $< 5 \times 10^8$ K if the Urca shell neutrino emissivity is included; and for both mass models the temperature has a significant local minimum at the location of the Urca shell (see Extended Data Fig. 2).

This has important implications for the ignition of superbursts, which are thought to be triggered by the unstable thermonuclear reaction $^{12}$C + $^{12}$C. The observed recurrence times, of the order of one year, are much shorter than predictions of current models\textsuperscript{10,15}, which indicates that the temperature at the ignition depth is underestimated. The presence of Urca shells implies that this observation does not point to an unexpectedly hot crust\textsuperscript{2,10}. Because of the Urca shells, we conclude that the standard carbon-ignition scenario for superbursts requires a powerful, as yet unknown, heat source that operates at surprisingly shallow densities $\lesssim 10^{10}$ g cm$^{-3}$ very near the carbon ignition layer. Alternatively other, more exotic, mechanisms would have to be found to ignite and power superbursts.

Urca shell cooling therefore forces fundamental changes in current superburst models. Realistic ignition conditions must now include a strong localized heat source at a depth close to that of ignition, with a strong heat flux flowing inwards into the Urca shell cooling layer. The resulting temperature profile at ignition is therefore dramatically different from that assumed previously, which may alter predicted light curves. In addition, during the explosion, the temperature at the ignition depth rises to $\sim 10^9$ K. Heat from this layer will diffuse inward; on the basis of the thermal diffusion timescale in the neutron star crust\textsuperscript{17}, we estimate that in the absence of any neutrino emission, the temperature would rise to $\sim 10^9$ K at the depth of the Urca shell within a day following ignition. The presence of a strong ‘heat sink’ at that depth, however, will prevent the deeper layers from rising in temperature and will, therefore, force the observed light curve to decay faster than expected over timescales of roughly one day. Current superburst observations on this timescale are rare and provide data of limited quality\textsuperscript{26}, but a dedicated programme of superburst follow-up observations with current instrumentation could address this problem. Detailed simulations, which are beyond the scope of this Letter, are required to quantify the effect of Urca shell cooling on superburst light curves.

Another observational signature might be found in neutron star cooling following an accretion outburst. Unlike crustal heating, the rate of Urca shell cooling does not scale with accretion rate, but rather depends only on temperature. Cooling will therefore continue in transiently accreting neutron stars once accretion has ceased, and might affect observations of the cooling crusts in the hottest of these systems, such as XTE J1701–462\textsuperscript{27}; in such systems, the Urca shell neutrino cooling rate is comparable to typical photon luminosities of $10^{32}–10^{33}$ erg s$^{-1}$ for typical initial crust temperatures of $(1–3) \times 10^8$ K.

**Online Content** Any additional Methods, Extended Data display items and Source Data are available in the online version of the paper; references unique to these sections appear only in the online paper.

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**Figure 3 | Neutrino luminosities in the accreted neutron star crust.** For purposes of comparison, estimates of the neutrino luminosities were obtained by integrating the corresponding emissivities over a neutron star crust with a constant local temperature, following the methodology of ref. 10. Although an actual neutron star crust is not isothermal, the temperature variation across the crust is not large (typically less than a factor of 2). The Urca-shell luminosities were calculated for superburst ashes\textsuperscript{26} (solid red line), X-ray burst ashes produced by the rapid proton-capture (rp) process\textsuperscript{17} (dashed red line), and a pure $^5$He composition (dotted red line) to demonstrate the maximum effect.

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Supplementary Information is available in the online version of the paper.

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Author Contributions H.S. calculated crust models, analysed data and prepared the manuscript. S.G. developed and implemented the phase space calculation. S.G. and P.M. calculated the weak transition rates. E.F.B. calculated crust temperature profiles and assisted with writing the manuscript. A.T.D. computed the temperature scaling of the neutrino emission. L.K. calculated superburst models. M.B., W.R.H. and R.L. wrote model code. All authors contributed to the interpretation of the results, and contributed to or commented on the manuscript.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to H.S. (schatz@nscl.msu.edu).
Extended Data Figure 1 | Calculated proton and neutron single-particle energy levels in $^{105}\text{Zr}$ as functions of nuclear deformation. Left panel, proton levels; right panel, neutron levels. The 40 protons and 65 neutrons in $^{105}\text{Zr}$ fill all levels up to the Fermi levels corresponding to these nucleon numbers in the two diagrams (red dots). Levels corresponding to even parity are shown as solid lines, those corresponding to odd parity as dashed lines. Shell gaps are characterized by a particularly large separation in energy between two adjacent single-particle levels. The numbers of protons or neutrons that occupy levels up to the shell gap are indicated by circled numbers. The single-particle levels are shown for a spherical nucleus in spectroscopic standard notation (left side of each panel), and for a deformation near the calculated ground-state shape of $^{105}\text{Zr}$ with quadrupole and hexadecapole shape-parameter values $e_2 = 0.333$ and $e_4 = 0.06$, respectively$^{28}$ (right side of each panel). The middle section of each panel shows the change in level energies as $e_2$ and $e_4$ change from spherical values $e_2 = e_4 = 0$ to deformed values$^{28}$. The well-known “magic numbers” 50 and 82 corresponding to particularly large gaps stand out at zero deformation$^{29}$. When the nuclear shape becomes deformed, the spherical shell gaps disappear resulting in a large density of levels in the vicinity of the Fermi level. This gives rise to a large number of states at low excitation in $^{105}\text{Zr}$. Some of these states can be populated by strong $\beta^-$ decay transitions from the ground state of $^{105}\text{Y}$. The situation is similar for the electron capture on $^{105}\text{Zr}$ into deformed $^{105}\text{Y}$.

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Extended Data Figure 2 | Temperature as a function of depth in the accreted neutron star crust for different Urca shell cooling strengths. Here we use $P/g = \int \rho \, dz$ as a proxy for depth, where $P$ is the pressure, $g$ the local gravitational acceleration, $\rho$ the mass density and $z$ the spatial depth coordinate. As a baseline model, we fix the temperature to be $T = 0.42$ GK at $P/g = 10^9$ g cm$^{-2}$ and $T = 0.35$ GK at the crust–core transition. In the absence of Urca shell cooling, the peak local temperature reaches 0.73 GK (solid curve) with the temperature at the superburst ignition depth ($P/g = 10^{12}$ g cm$^{-2}$) being 0.66 GK. With the addition of cooling using the HFB-21 mass model and a superburst ash composition (blue dotted line), a local temperature minimum, $T = 0.33$ GK, appears at the location of the Urca shell. Indeed, for these conditions the temperature at the Urca shell is lower than that at the upper boundary, so that a temperature inversion develops. Even for the much lower Urca shell emissivity of the FRDM mass model (blue dashed line), the temperature at the depth of the superburst ignition is $\leq 5 \times 10^8$ K, which is inconsistent with typical superburst ignition conditions. For both mass models, the temperature has a local minimum at the location of the Urca shell. The steady-state cooling luminosity from the shell is $2 \times 10^{35}$ erg s$^{-1}$ for the HFB-21 mass model and $1.4 \times 10^{35}$ erg s$^{-1}$ for the FRDM mass model. As a result, the Urca shell thermally decouples the envelope of light elements from the heating in the deeper crust.