BRIEF COMMUNICATIONS

Circadian organization in reindeer

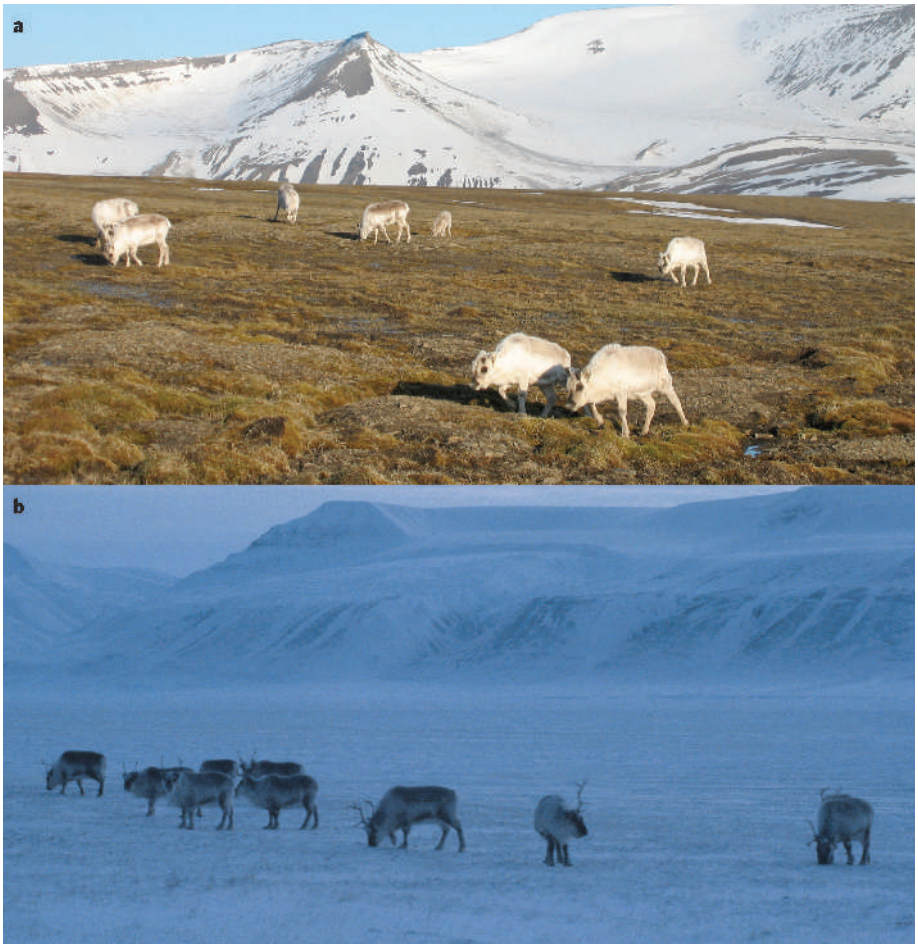
These Arctic animals abandon their daily rhythms when it is dark all day or light all night.

The light/dark cycle of day and night synchronizes an internal 'biological clock' that governs daily rhythms in behaviour, but this form of regulation is denied to polar animals for most of the year. Here we demonstrate that the continuous lighting conditions of summer and of winter at high latitudes cause a loss in daily rhythmic activity in reindeer living far above the Arctic Circle. This seasonal absence of circadian rhythmicity may be a ubiquitous trait among resident polar vertebrates.

Circadian oscillators are present in all organisms on our rotating planet (see ref. 1, for example). These 'biological clocks' govern the temporal organization of physiological functions and behaviour, and enable plants and animals to anticipate and prepare for daily events such as sunrise and sunset[2]. A convincing argument for the internal nature of circadian regulation is the persistence of temporal organization under constant environmental conditions. This was first described in the plant *Mimosa pudica* by the French astronomer Jean de Mairan in 1729 (ref. 3), and persistence, under constant conditions, of rhythms with periods deviating slightly from 24 h remains a prerequisite for the identification of circadian control.

Few plants and animals experience constant conditions in the wild. But at high latitudes, where the Sun neither sets in summer nor rises in winter, resident polar organisms experience the distinct changes in light intensity that result from a day/night cycle for just a few weeks each year — in spring and in autumn. We recorded daily patterns of activity continuously for one year in two subspecies of reindeer: *Rangifer tarandus platyrhynchus* (5 or 6 animals; Fig. 1a, b) living at 78° N in the high Arctic archipelago of Svalbard, and *R. t. tarandus* (6 animals) living in northern Norway at 70° N. The animals ranged freely in their natural habitat. (For methods, see supplementary information.)

All animals showed alternating bouts of activity and inactivity typical of ruminants[4]; these cycles were substantially shorter than 24 hours (ultradian) and persisted throughout the year. Plots of activity over time (actograms) reveal a complete absence of circadian organization of this behaviour in both subspecies in summer and in Svalbard reindeer in winter (Fig. 1c, d). Evidently, the changes in light intensity that occur across the day at these times are not sufficient to synchronize



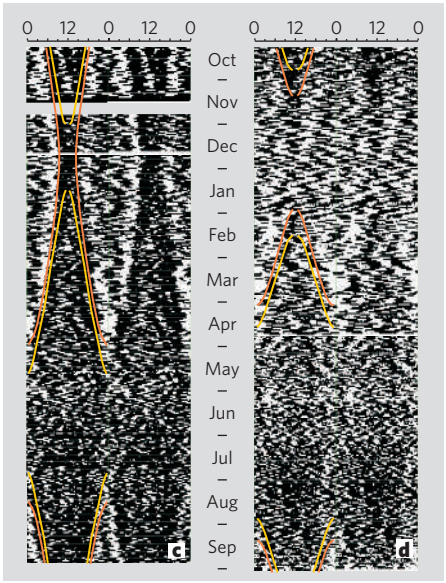


Figure 1 | Activity patterns in reindeer under polar light conditions. **a, b,** Polar light conditions: mixed groups of Svalbard reindeer *Rangifer tarandus platyrhynchus* at 78° N, at **a**, midnight in late June, and **b**, midday in mid-February. **c, d,** Sample actograms showing patterns of activity over one year in sub-adult reindeer in **c**, northern Norway (*R. t. tarandus*, 70° N; $n = 1$), and **d**, Svalbard (*R. t. platyrhynchus*, 78° N; $n = 1$). Data, recorded continuously using small activity-loggers, are presented as double-plot actograms in which each row represents two consecutive days; time of day is indicated. Bouts of activity (black bars) are interspersed with bouts of inactivity (white spaces). Grey region, data missing. Lines indicating the beginning and end of civil twilight (when light intensity is 10 lux, orange) and sunrise and sunset (yellow) are superimposed on each actogram. Rhythmicity in the actograms was determined by F-periodogram analysis (see supplementary information).

the pattern of activity in reindeer. However, the daily pattern was modified when there was a distinct light/dark cycle, and reindeer in northern Norway, in particular, displayed a significant rhythm of exactly 24 hours throughout autumn, winter and spring (see supplementary information).

Free-living reindeer do not therefore show evidence of the classical prerequisite for circadian organization— persistence under constant conditions. Seasonal absence of rhythmicity in the circadian range has been recorded in the daily activity of the Svalbard ptarmigan (*Lagopus mutus hyperboreus*)[5], and in circulating levels of the hormone melatonin in ptarmigan[6] and in reindeer[7], indicating that the expression of an internal clock is reduced in both Arctic species under constant light conditions. We therefore suggest that seasonal absence of circadian rhythmicity is a ubiquitous trait among resident polar vertebrates.

Reduced circadian organization may enhance animals' responsiveness and speed of phase adaptation to the light/dark cycle, as proposed for migrating birds[8] and mammals emerging from hibernation[9]. And for herbivores in polar regions, there can be little selective advantage in maintaining strong internal clocks in an effectively non-rhythmic environment.

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WORLD YEAR OF PHYSICS

A direct test of $E = mc^2$

One of the most striking predictions of Einstein's special theory of relativity is also perhaps the best known formula in all of science: $E = mc^2$. If this equation were found to be even slightly incorrect, the impact would be enormous — given the degree to which special relativity is woven into the theoretical fabric of modern physics and into everyday applications such as global positioning systems. Here we test this mass–energy relationship directly by combining very accurate measurements of atomic-mass difference, Δm, and of γ-ray wavelengths to determine E, the nuclear binding energy, for isotopes of silicon and sulphur. Einstein's relationship is separately confirmed in two tests, which yield a combined result of $1 - \Delta mc^2/E = (-1.4 \pm 4.4) \times 10^{-7}$, indicating that it holds to a level of at least 0.00004%. To our knowledge, this is the most precise direct test of the famous equation yet described.

Our direct test is based on the prediction that when a nucleus captures a neutron and emits a γ-ray, the mass difference Δm between the initial (including unbound neutron) and final nuclear states, multiplied by c^2 (where c is the speed of light), should equal the energy of the emitted γ-ray(s), as determined from Planck's relation $E = hf$ (where h is Planck's constant and f is frequency).

The total energy of the γ-rays emitted as the daughter nucleus decays to the ground-state was determined by summing the individual γ-ray energies. These were obtained by wavelength measurement using crystal Bragg spectroscopy. The mass difference Δm is measured by simultaneous comparisons of the cyclotron frequencies (inversely proportional to the mass) of ions of the initial and final isotopes confined over a period of weeks in a Penning trap.

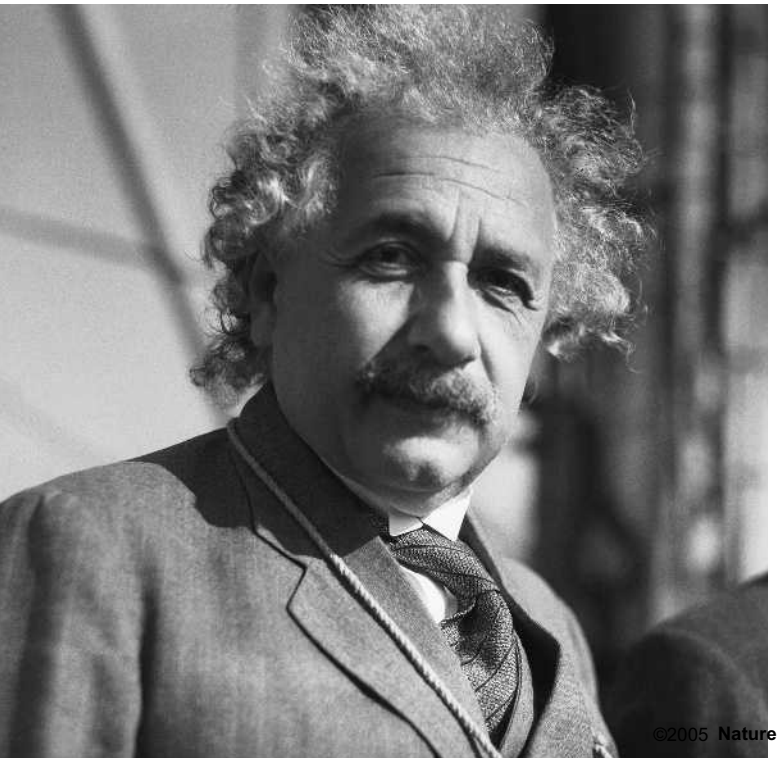
For an atom X with a mass number of A undergoing this nuclear reaction, the comparison is expressed in terms of measured quantities as

$$\Delta Mc^2 = (M[^{A}\mathrm{X}] - M[^{A+1}\mathrm{X}] + M[\mathrm{D}] - M[\mathrm{H}])c^2 = 10^3 N_A h(f_{A+1} - f_{\mathrm{D}})\ \mathrm{mol\ AMU\ kg^{-1}} \quad (1)$$

where the Avogadro constant N_A relates the measured mass M[X] in unified atomic mass units (AMU) to its mass in kilograms m[X]. We made comparisons for $^{A+1}\mathrm{X} = {}^{29}\mathrm{Si}$ and $^{A+1}\mathrm{X} = {}^{33}\mathrm{S}$. The mass of the neutron $M[n]$ is determined from the masses[1] of hydrogen M[H] and deuterium M[D] combined with f_{D}, the frequency of the γ-ray corresponding to the deuteron binding energy[2]. The molar Planck constant is $N_A h = 3.990312716(27) \times 10^{-10}$ J s mol^{-1}; numbers in parentheses indicate uncertainty on the last digits. This figure has been independently confirmed at about the 5×10^{-8} level by a range of experiments through its relationship with the fine-structure constant[1].

The γ-ray frequencies on the righthand side of equation (1) have been measured using the GAMS4 crystal-diffraction facility at the Laue–Langevin Institute in Grenoble[3]. The γ-rays emitted from sources located near the high-flux reactor core are diffracted by two nearly perfect, flat crystals whose lattice spacing, d, has been determined in metres[4]. The diffraction angles, θ, are measured with angle interferometers calibrated using a precision optical polygon (Fig. 1a). Wavelengths are determined from the Bragg equation $\lambda = 2d\sin\theta$ and were measured for the 3.5-MeV and 4.9-MeV transitions in ^{29}Si, for the 0.8-MeV, 2.4-MeV and 5.4-MeV transitions in ^{33}S, and for the 2.2-MeV transition in deuterium ^{2}H (see supplementary information).

Because the diffraction angle for a 5-MeV γ-ray by a low-order silicon reflection is less than 0.1°, our binding-energy determinations were limited by our ability to measure the diffraction angles of the highest-energy γ-rays with fractional accuracy better than about



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Albert Einstein: father of the famous formula.