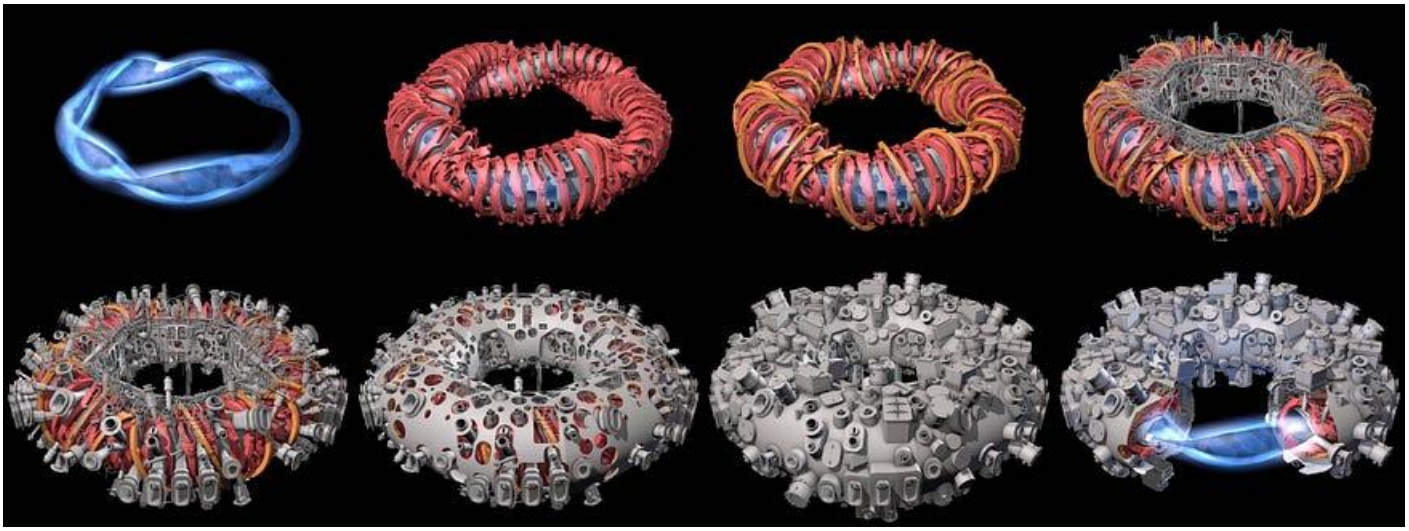
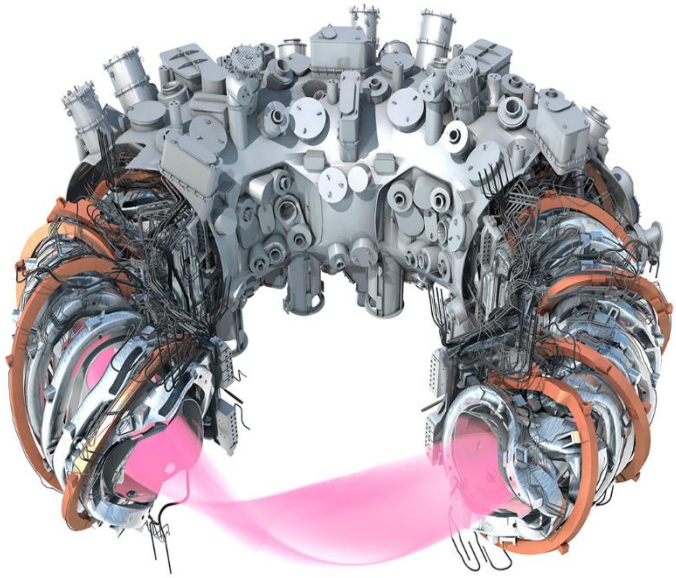
CLEAN ENERGY VOL 3

The Future Of Fusion?

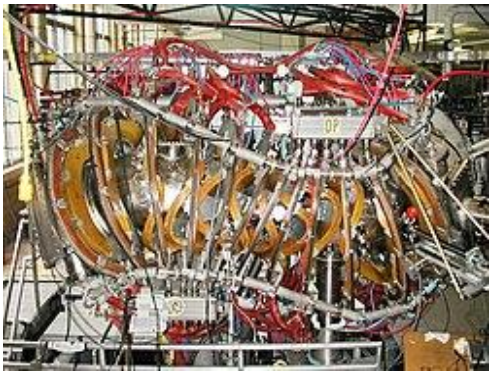
Meet The Stellarator





Example of a stellarator design, as used in the Wendelstein 7-X experiment: A series of magnet coils (blue) surrounds the plasma (yellow). A magnetic field line is highlighted in green on the yellow plasma surface.Wendelstein7-X in Greifswald, Germany. Coils are prepared for the experimental stellarator. HSX stellarator

A **stellarator** confines plasma using external magnets. Scientists aim to use stellarators to generate fusion power. It is one of many types of magnetic confinement fusion devices. The name "stellarator" refers to stars because fusion mostly occurs in stars such as the Sun.[1] It is one of the earliest human-designed fusion power devices.



The stellarator was invented by American scientist Lyman Spitzer in 1951. Much of its early development was carried out by Spitzer's team at what became the Princeton Plasma Physics Laboratory (PPPL). Spitzer's Model A began operation in 1953 and demonstrated plasma confinement. Larger models followed, but demonstrated poor performance, losing plasma at rates far worse than theoretical predictions. By the early 1960s, hopes of producing a commercial machine faded, and attention turned to studying fundamental theory. By the mid-1960s, Spitzer was convinced that the stellarator was matching the Bohm diffusion rate, which suggested it would never be a practical fusion device.

The release of information on the USSR's tokamak design in 1968 indicated a leap in performance. After debate within the US industry, PPPL converted the Model C stellarator to the Symmetrical Tokamak (ST) as a way to confirm or deny these results. ST confirmed them, and large-scale work on the stellarator concept ended in the US replaced by tokamaks. Research continued in Germany and Japan, where several new designs were built.

The tokamak ultimately proved to have problems similar to the stellarators, but for different reasons. Since the 1990s, the stellarator design has seen renewed interest.[2] New methods of construction have increased the quality and power of the magnetic fields, improving performance.[3] A number of new devices have been built to test these concepts.

A stellarator is a machine that uses magnetic fields to confine plasma in the shape of a donut, called a torus. These magnetic fields allow scientists

to control the plasma particles and create the right conditions for fusion reactions. The stellarator is one of the technologies scientists believe could lead to real-world fusion power. The helical-twisted magnetic field, necessary for successful plasma confinement, is generated only by magnetic coils of various shapes.

The **stellarator** was invented by **American scientist Lyman Spitzer** in **1951**. It seeks to confine fully ionized plasms by means of intricately shaped magnetic fields in all three dimensions of space. The concept has been studied theoretically and experimentally ever since.

Deep in Greifswald, Germany, scientists are working on a machine that could one day power the entire world — without fossil fuels, smoke, or even sunlight. It's called Wendelstein 7-X — a fusion reactor so advanced, it bends plasma with magnetic fields shaped like twisted spirals, mimicking the Sun's core.

This isn't science fiction. It's nuclear fusion, the process that powers stars. No carbon emissions. No long-term radioactive waste. Just the same energy that lights up the universe — contained in a machine on Earth.

Recently, it set a world record for maintaining superhot plasma for 43 seconds — a huge leap for a device not even built to generate electricity yet. It's not ready to power cities, but it's a glimpse of what could come: near-infinite energy from a pinch of hydrogen.

Imagine a future where war over oil is obsolete. Where blackout is a word in the history books. Where the power of stars is at our fingertips. That future is being shaped now — not in Silicon Valley, but in a quiet lab in Germany. The question is… will we invest in it before it's too late?

Electrical Power from Hydrogen to Dark Matter

Brilliant Light Power has developed a new commercially competitive, non-polluting, plasma-based primary source of massive power from the conversion of hydrogen atoms of water molecules to dark matter, the previously unidentified matter that makes up most of the mass of the universe. The SunCell® that was invented to harness the new power source catalytically converts hydrogen directly into dark matter form called Hydrino® releasing brilliant high-energy light which is down-converted in energy to facilitate the production of electricity using commercially-available concentrator photovoltaic cells.

A Current Commercial Design SunCell®

The Power of the SunCell®

The electricity producing SunCell® uses a catalyst to cause hydrogen atoms of water molecules to transition to the lower-energy Hydrino® states by allowing their electrons to fall to smaller radii around the nucleus. This results in a release of energy that is intermediate between chemical and nuclear energies and a nonpolluting product. The energy release of the hydrogen separated from H2O, that can be acquired even from the humidity in the air, is over one hundred times that of an equivalent amount of high-octane gasoline. The highest known power density with direct electricity conversion facilitates essentially all power applications untethered to fuels or grid infrastructure. The electrical generation cost is anticipated to be less than 10% that of any known power source.

The World's First Continuous Plasma – Closed SunCell®

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Electron paramagnetic resonance proof for the existence of molecular hydrino

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Highlights

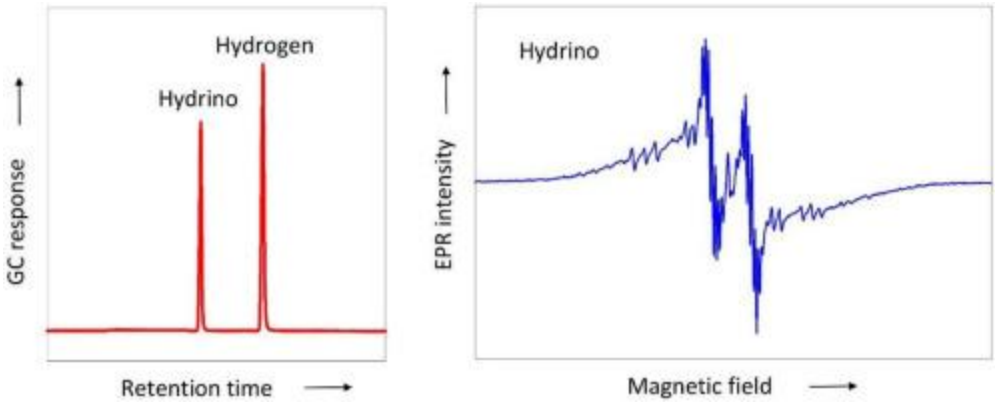
- •
  New allotrope of molecular hydrogen recoded by EPR.
- •
  New molecular orbital structure confirmed having a paired and an unpaired electron.
- •
  SQUID behavior noted for a molecular orbital.
- •
  New fastest gas migration velocity recorded by gas chromatography.
- •
  New state of molecular hydrogen is the basis of a new power source.

Abstract

Quantum mechanics postulates that the hydrogen atom has a stable ground state from which it can be promoted to excited states by capture of electromagnetic radiation, with the energy of all possible states given by $E_n = -13.598/n^2$ eV, in which $n \geq 1$ is a positive integer. It has been previously proposed that the $n = 1$ state is not the true ground state, and that so-called hydrino states of lower energy can exist, which are characterized by fractional quantum numbers $n = 1/p$, in which $1 < p \leq 137$ is a limited integer. Electron transition to a hydrino state, H(1/p) is non-radiative and requires a quantized amount of energy, $2mE_1$ (m is an integer), to be transferred to a catalyst. Numerous putative hydrino-forming reactions have been previously explored and the products have been characterized by a range of analytical methods. Molecular hydrino has been predicted to be paramagnetic. Here, we give an account of an electron paramagnetic resonance (EPR) study of molecular hydrino $H_2(1/4)$ that was produced as gaseous inclusion in polymeric Ga(O)OH by a plasma reaction of atomic hydrogen with non-hydrogen bonded water as the catalyst. A sharp, complex, multi-line EPR spectrum is found, whose detailed properties prove to be consistent with predictions from hydrino

theory. Molecular hydrino was also identified in gas chromatography as a compound faster than molecular hydrogen.

Graphical abstract



Introduction

The quantized energy levels of the hydrogen atom are $E_n = -13.598/n^2$ eV, in which the principal quantum number n is a positive integer. The electronic ground state has n = 1. Higher states can be populated by absorption of light according to the Rydberg equation $\nu = R_H[(1/n_2)^2-(1/n_1)^2]$ with $R_H = 109.677$ cm^{-1}. R. Mills has hypothesized and experimentally tested that the n = 1 state is not the absolute ground state and that lower-energy hydrino states characterized by fractional quantum numbers 1/p, with $2 = p \leq 137$, can exist. The underlying theory has been presented in a series of papers [[1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11]]. A comprehensive compilation of the theory, known as The Grand Unified Theory of Classical Physics (GUTCP) is available as a 3-vol e-book with regular updates [12]. Ample experimental evidence has been presented by the Mills lab that H(1/p) can be produced from H(n = 1) in a non-radiative process whereby a catalyst reversibly takes up an amount of energy equal to $(p-1) \times 27.196$ eV such that a total amount equal to $(p^2-1) \times 13.598$ eV is ultimately released as heat, continuum EUV emission, energetic signatures, and hydrino chemical products [[13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39]], [[40], [41], [42], [43], [44], [45], [46], [47], [48], [49], [50], [51], [52], [53], [54], [55], [56], [57], [58], [59], [60], [61], [62], [63], [64], [65], [66], [67], [68], [69], [70]].

Mills' GUTCP theory has been evaluated – both positively and negatively – by others, however, thus far only on the basis of theoretical arguments [[71], [72], [73], [74], [75], [76], [77], [78], [79], [80], [81], [82], [83], [84]]. Experimental support for the existence of hydrino, as H, H^-, or H_2, has been presented by the Mills lab and other independent laboratories and researchers [[13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39]], [[40], [41], [42], [43], [44], [45], [46], [47], [48], [49], [50], [51], [52], [53], [54], [55], [56], [57], [58], [59], [60], [61], [62], [63], [64], [65], [66], [67], [68], [69], [70]] using

vibrating sample magnetometry, magic angle spinning ^{1}H nuclear magnetic resonance spectroscopy (MAS H1 NMR), Raman spectroscopy including deuterium substitution, photoluminescence emission spectroscopy, Fourier transform infrared spectroscopy (FTIR), gas chromatography, X-ray photoelectron spectroscopy (XPS), time of flight secondary ion mass spectroscopy (ToF-SIMS), electrospray ionization time of flight mass spectroscopy (ESI-ToFMS), and high performance liquid chromatography (HPLC). The energetics of the hydrino reaction was confirmed by the observation of extraordinarily Doppler and Stark H line broadening, hydrogen plasma afterglow, ultraviolet and visible spectroscopy of population inversion, shockwave formation, 20 MW-level continuum EUV optical power wherein the reaction rate was greatly increased by applying an arc current to recombine ions and electrons formed by the energy transfer to HOH that is consequently ionized, differential scanning calorimetry of hydrino solid-fuel reactant mixtures, electrical energy balance of hydrino reaction electrochemical cells, and water bath calorimetry on so-called SunCells® comprising a molten gallium injector that electrically shorts two plasma electrodes with the molten gallium to maintain an arc current plasma state that boosted output power to 340,000 W in a 0.5 -liter reactor volume. The present study significantly extends this body of research as it is carried out in an independent laboratory with a technique, EPR, not previously applied in hydrino studies.

Experimental

Full experimental details are given in the ESI. These include descriptions of plasma reactor setup, production of reactants, reaction control, and product processing. Analytical methods for product analysis are detailed covering gas chromatography, scanning electron microscopy, energy dispersive X-ray spectroscopy, Rutherford backscattering spectrometry, time-of-flight secondary ion mass spectrometry, transmission electron microscopy, and X-ray diffraction. The EPR spectroscopy is described including all in-house developed software for data analysis.

Results and discussion

Molecular hydrino sample production

A common feature of a hydrino state and an excited H state is that both comprise an electron, a proton, and a photon. In an excited H state, the photon superimposes the proton field to decrease the central field at the electron to + e/n (e is the fundamental charge) and creates a radial dipole instability that results in radiation. Conversely, the photon of a hydrino state increases the central field at the electron to +(1+m)e and creates a radial monopole that is radiatively stable. According to GUTCP, ground-state (n = 1) atomic hydrogen can be converted to atomic hydrino (n = 1/(1+m)) by means of a nonradiative resonant energy transfer to a catalyst with potential energy = m × 27.2 eV (that is 2 m × E_1) according to the reactionm × 27.2 eV + H(1) + Cat →
H∗(1/(1+m)) + Cat∗ + m × 27.2 eV

in which the energy term on the left is energy absorbed by the catalyst (typically by resonant ionization) and the term on the right is the energy released by the increase in the potential energy of the hydrogen atom to form $H*(1/(1+m))$, an intermediate of the hydrino atom of radius a_H. Subsequently the ionized catalyst, $Cat*$, regenerates by recombination, with the release of its previously gained ionization energy, and the hydrino intermediate converts to stable $H(1/(m+1))$ having a radius of $a_H/(1 + m)$ by release of additional energy such that the overall release of energy is $[(m+1)^2-1] \times 13.6$ eV. By considering the quantum state $p = m + 1$ the reaction may be written $H(1) \rightarrow H(1/p) + (p^2-1) \times 13.6$ eV

The hydrino transition reaction requires atomic H and a single catalyst species which is typically formed chemically or by a plasma reaction [[13], [14], [15], [16], [17], [18], [19], [20]]. Further reactivity produces molecular hydrino $H_2(1/p)$ from atomic hydrino $H(1/p)$ when the bond energy is removed by collision with a third body, which can be a reactor-wall constituent [85]. A variety of species can resonantly and nonradiatively accept $m \times 27.2$ eV from atomic hydrogen to serve as catalyst for hydrino formation; in the present case we use the nascent (that is, in situ prepared, not hydrogen-bonded) water molecule with potential energy 3×27.2 eV [13,14]. Details of the sample preparation are given in ESI. Briefly, the reactor is a closed vessel in which a low-voltage discharge is created between a liquid gallium electrode and a solid tungsten electrode with water and hydrogen introduced from a supported-Pt H_2/O_2 recombiner supplied with H_2 gas and trace O_2 to form trace nascent, or non-H-bonded water catalyst. Either additional oxygen or water vapor are introduced to produce gallium oxide that is collected. Regular $H_2(1)$ is known to absorb onto Ga_2O_3 [[86], [87], [88]]. It is unknown if molecular hydrino putatively associated with the Ga_2O_3 is sufficiently stable to survive slow transfer to an EPR lab because the Ga_2O_3 collected from the SunCell® reactor is contaminated with metallic gallium along with Ga(O)OH. The presence of gallium metal precludes EPR spectroscopy on the mixture. However, high-purity crystalline Ga(O)OH for EPR analysis is isolated as follows. After dissolution of the mixture of gallium metal, gallium oxide, and Ga(O)OH in 4 M KOH, a unique non-soluble product comprising Ga(O)OH in the form of an aggregate of micro-spheres containing molecular hydrino $H_2(1/4)$ slowly polymerizes as shown by scanning electron microscopy (SEM) and transmission electron microscopy (TEM) in Fig. 1. We denote this stabilized system by $H_2(1/4)$@Ga(O)OH compliant with a common notation for atomic hydrogen occluded in solid hosts [89,90].

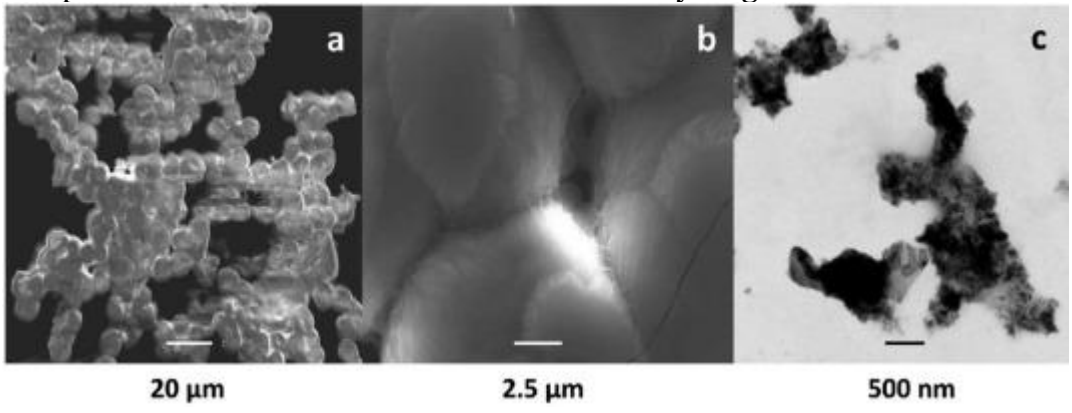


Fig. 1. Scanning electron microscopy and transmission electron microscopy of $H_2(1/4)$@Ga(O)OH. Trace a: SEM at 800 × magnification showing chains of microspherical particles; trace b: SEM showing 5 μm width of the particles, each comprising very fine fibers; trace c: TEM imaging of morphologically polymeric crystals of hexagonal structure (Fig. S3), which were very sensitive to the TEM electron beam. Observed spherical particles have approximately 100 nm average diameter.

Energy dispersive X-ray spectroscopy (EDS) showed an elemental composition of $GaO_{2.1}$ (Fig. S1). Conventional elemental analysis of H relies on combustion to H_2O. However, $H_2(1/4)$ theoretically and experimentally does not undergo combustion with oxygen. The molecular orbital electron energy level is too low to react with oxygen. Therefore, Rutherford backscattering spectrometry (RBS) was performed on the $H_2(1/4)$@Ga(O)OH which identified the composition as $GaO_{1.68}H_{1.32}$ with a density of 8.56×10^{22} atoms/cm^2 corresponding to an excess H content, some of which is hydrino hydrogen, based on the results of gas chromatographic identification and EPR spectroscopy reported below. Time-of-flight secondary ion mass spectrometry (ToF-SIMS), presented in Fig. S2, showed Ga in the positive ion spectrum and O and H as dominant ions in the negative ion spectrum wherein the hydride ion was elevated compared to control Ga(O)OH. No hydrocarbons above adventitious levels were present and no nitrogen was found indicating the unlikeliness for EPR signals to originate from organic radicals. Equally, in the positive spectrum no potentially paramagnetic transition ions were present. Selected area electron diffraction (SAED) with the transmission electron microscope (Fig. S3) revealed the samples to comprise two different morphological and crystalline forms of Ga(O)OH: rods with orthorhombic diffraction pattern matched control Ga(O)OH, which lacks molecular hydrino, in morphology and crystalline structure [91] and were not sensitive to the TEM electron beam; on the other hand, morphologically polymeric crystals comprising hexagonal crystalline structure were very electron-beam sensitive, and were assigned to novel $H_2(1/4)$@Ga(O)OH. X-ray diffraction (XRD) showed a phase shift from the Ga(O)OH control lines with different deviations between NaOH and KOH formed $H_2(1/4)$@Ga(O)OH as illustrated in Fig. S4.

Gas chromatography of molecular hydrino

The $H_2(1/4)$ molecule has a cross section that is circa 1/64 of that of the helium atom. By consequence it is difficult to store molecular hydrino in a container for extended periods of time. Also, the here employed production scheme always results in contamination with regular $H_2(1)$. $H_2(1/4)$ was identified by gas chromatography in two complementary experiments. $H_2(1/4)$ gas was collected from the SunCell® reactor using a valved microchamber connected to the vacuum line and cooled to 15 K by a cryopump system. The liquefied gas was warmed to room temperature to achieve 10 Torr chamber pressure and was injected into a gas chromatograph. $H_2(1/4)$ was observed as an early peak at 8.31 min and hydrogen that co-condensed with H_2 gas was observed at 12.87 min (Fig. 2a).

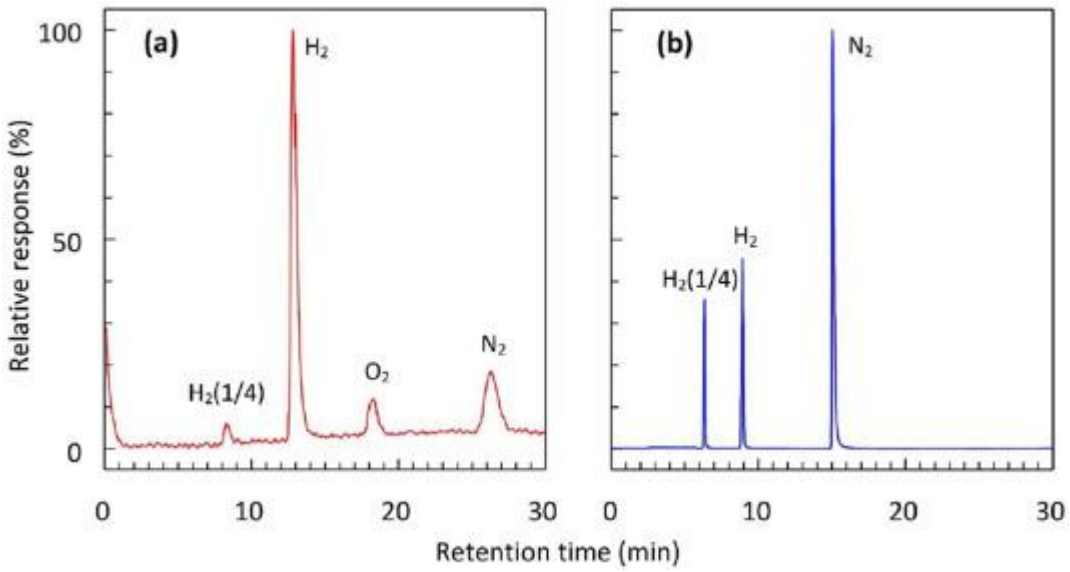


Fig. 2. Gas chromatographic identification of molecular hydrino $H_2(1/4)$. Trace a: GC of gas collected from the SunCell® reactor with a cryopump showing $H_2(1/4)$ at 8.31 min. Trace b: the GC of hydrino gas evolved by heating the KOH-treated Ga_2O_3/Ga(O)OH material collected from the SunCell® to 800 °C. The known hydrogen and nitrogen peaks were observed at ca 8 and 15 min and a novel peak at ca 6 min was assigned to $H_2(1/4)$.

The peak at 18.24 min is oxygen that was condensed before the SunCell® run to serve as a solvent for $H_2(1/4)$. The collected gas contained no helium by mass spectroscopy. The early peak was negative with a helium carrier gas indicating that the early peak had a higher thermal conductivity, and the migration rate was faster than that of helium with an argon carrier gas. No known gas has a faster migration rate and higher thermal conductivity than H_2 or He, which is characteristic of and identifies hydrino since it has a much greater mean free path due to exemplary $H_2(1/4)$ having 64 times smaller volume and 16 times smaller ballistic cross section. Hydrogen condensed under pressure and temperature conditions that violate the Clausius Clapeyron equation due to the raising of the H_2 liquefaction temperature by co-condensation with $H_2(1/4)$.

In a different experiment gas chromatography was performed on the gases released by thermal desorption of gas bound to the KOH-treated Ga_2O_3/Ga(O)OH sample originally collected from a SunCell® plasma run. Known gases such as hydrogen were also run to identify their migration times to compare to the results of the SunCell®-derived sample. The gas chromatograph of hydrino gas evolved by heating the Ga(O)OH material to 800 °C is shown in Fig. 2b. Note that the amplitudes of the peaks assigned to molecular hydrino in the experiments of Fig. 2 are not quantifiable: since $H_2(1/4)$ is not obtained in pure form, its effect on the thermal conductor sensor cannot be quantified.

Paramagnetism of molecular hydrino

Alternative to the probabilistic matter waves of quantum mechanics, the electron in a hydrogen atom is modelled in GUTCP as a two-dimensional spherical membrane of

infinitesimal thickness in which current flows along two infinite, nested rotation sets of great circle filaments. This current pattern naturally gives rise to both orbital and spin angular momentum wherein the latter defines a free-electron factor $g_e = 2.0023193$ [3,4,[7], [8], [9],12,13]. In the hydrogen molecule the spherical current pattern becomes a prolate spheroid in which the pairing of two electrons leads to a diamagnetic ground state. Atomic hydrino differs from H(n > 1) states in that rather than the absorption of a photon to form an excited state, H(n = 1/p) is formed by a non-radiative energy transfer to a resonant energy acceptor followed by continuum extreme ultraviolet radiation to the final stable hydrino atomic state. Two hydrino atoms react to form molecular hydrino having two photons that are phase-locked to the electron current and circulate in opposite directions. Consequently, the molecule has a diamagnetic and a paramagnetic electron, the latter with $g \neq g_e$ equal to $2 + 2 \times 0.0023193 = 2.0046386$ [92]. This fundamental prediction from first principles provides a unique, simple, and accurate testing criterion for the existence of molecular hydrino. Moreover, the theory predicts a specific and detailed splitting, or fine structure, of the g = 2.00464 resonance into a multi-line pattern due to internal magnetic and spin-orbit couplings affording a distinguishing EPR signature of molecular hydrino $H_2(1/4)$.

EPR spectroscopy of molecular hydrino

A wide magnetic field scan EPR spectrum of the Ga(O)OH solid powder taken at ambient temperature, exhibits a single derivative feature only against an essentially flat background, and with g value close to the free-electron value (Fig. 3a).

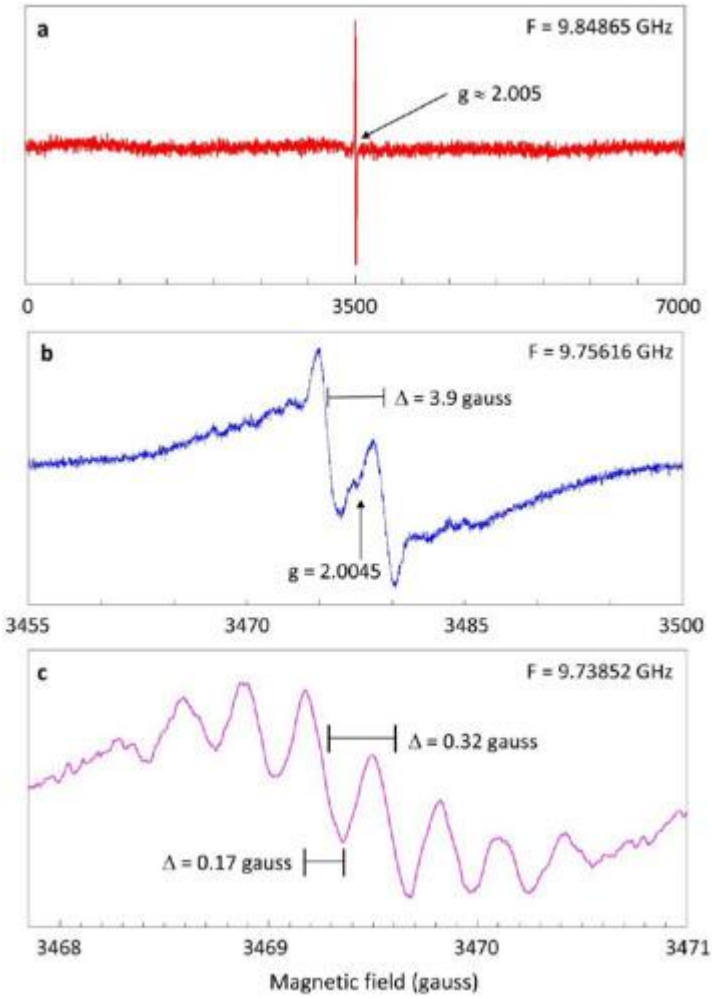


Fig. 3. EPR of postulated molecular hydrino $H_2(1/4)$ caged in solid Ga(O)OH polymer. Trace a: wide-scan overview spectrum showing a single feature only close to the free electron g value. Trace b: zoom-in of the single feature in trace a shows two main lines of equal intensity, separated by circa 4 gauss, and whose center is distinctly shifted from the free electron value to g = 2.0045. Trace c: further zoom-in on one of the lines now recorded with a very small modulation amplitude reveals a fine structure of multiple lines with apparent peak-to-peak derivative line width of 0.17 gauss and separated by circa 0.32 gauss. Data collection times for traces a-c were 10, 16, and 375 min, respectively. Modulation amplitudes were 1, 1, and 0.25 gauss, respectively. All spectra were taken at ambient temperature. Other experimental conditions are given in ESI.

Zooming-in on this feature (Fig. 3b) shows it to consist of two separate lines plus multiple weak signals in the low- and high-field wings. The center of the two main lines corresponds to an apparent g value of 2.0045(6) which is close to the value of 2.00464 predicted for the $H_2(1/4)$ S = 1/2 spin-only doublet system. The two lines are separated by circa 4 gauss and are of equal intensity. Microwave power saturation plots (Fig. S5) are very similar for the two peaks and are consistent with inhomogeneous broadening [93] (see below).

Concentrating on resolving fine structure in the main peaks we reduce the magnetic-field modulation amplitude to 25 mG (that is, below the bandwidth of the 100 kHz modulation frequency). The spectral amplitude in a single scan drops to below a signal-to-noise ratio of unity and extensive averaging over 6 h and filtering is required to afford the high-resolution pattern in Fig. 3c. Each line has resolved in an isotropic equidistant beat pattern with sub-line separation of circa 0.32 gauss.

For individual sub-lines we observe an apparent peak-to-peak width of circa 170 mG which is highly unusual for solid-state samples. Such narrow lines have only been found for (i) organic radicals in organic solvents at ambient temperature [94]; (ii) small paramagnetic molecules in matrices of noble gasses solidified at cryogenic temperatures [95]; (iii) single hydrogen atoms encapsulated in molecular cages [96]; and (iv) paramagnetic molecules in the gas phase at low pressure [97]. Excluding the first two options on obvious grounds (no organic solvents and no cryogenic temperatures) and the third one on spectroscopic grounds (atomic hydrogen EPR is a single line at the free electron g_e value split by over 500 gauss through proton hyperfine interaction), the narrow line width that we observe would only be consistent with the detection of a low-pressure paramagnetic gas occluded in a solid.

We recorded the spectrum in Fig. 4a under optimized conditions for the detection and resolution of satellite lines whose existence was indicated by the small periodic peaks in the wings of the spectrum in Fig. 3b. Thus, the fine structure of the two central lines was slightly deformed by over-modulation, and the data collection was extended to 40 h with constant frequency monitoring for subsequent correction of individual 4-min traces for minor frequency drift. The spectrum has been reproduced completely in duplicate on two different spectrometers in a lab of the spectrometer's manufacturer (Bruker, Billerica, MA, USA) [13]. The spectrum of Fig. 4a is stable for at least two years; it is reproducible over 11 samples produced in 11 reactor runs (Fig. S6), and the spectrum of an empty tube is a straight baseline (Fig. S6).

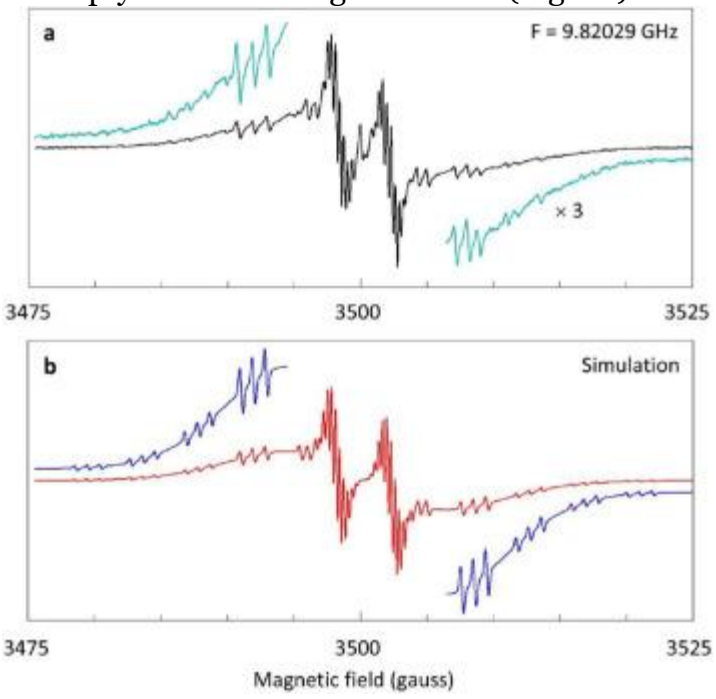


Fig. 4. Full EPR spectrum at high resolution of molecular hydrino $H_2(1/4)$. Trace a: extensively averaged spectrum (2400 min) taken under conditions optimized for maximal signal-to-noise ratio at the expense of minor over-modulation (0.2 gauss), exhibits a complex pattern of triplet satellite lines. Trace b is a simulation using field positions predicted by hydrino theory.

In spin quantification (ESI) we find that a complete spectrum of high resolution, such as in Fig. 4a, represents an S = 1/2 concentration of circa 2.6 μM if the paramagnet would be homogeneously distributed over the sample volume. Transmission electron microscopy (Fig. 1) and XRD show the Ga(O)OH polymer to comprise micro-spherical particles of the order of 100 nm diameter with an estimated spatial occupancy of roughly 10%. This would make the actual concentration of the $H_2(1/4)$ gas in occlusion very approximately 26 μM, which is equivalent to a partial pressure of circa 6×10^{-4} bar, qualitatively consistent with the observed narrow EPR line width [94,98]. Even if regular H_2 would co-occlude at, say, atmospheric pressure the small cross section for collision of molecular hydrino $H_2(1/4)$ would ensure a low collision frequency in agreement with the observed line width.

Simulation of the fine structure in spectrum Fig. 3c indicated the line shape to be Gaussian within the limitation set by the overlap of individual lines. The sets of satellite lines are better separated, and analysis of the first down-field triplet clearly shows the line shape to be essentially Gaussian (Fig S7). This implies inhomogeneous broadening, consistent with the power-saturation analysis (Fig. S5), and could be caused by interaction of hydrino molecules with the inner 'wall' of the inorganic polymer cage. In turn, this would imply the real lifetime line width from gas collision to be significantly less than the observed 170 mG inhomogeneous line width.

Interpretation of molecular hydrino EPR

Molecular hydrino comprises two protons at the foci of a two-electron prolate spheroid molecular orbital membrane, and an absorbed photon. The latter splits into two photons that are phase locked with the oppositely directed current patterns of the two electrons each consisting of an angularly distributed infinite ensemble of closed grand ellipse filaments of moving charge of an equipotential, minimum energy membrane surface [92]. Under this model exact solutions of a fine structure in the EPR ensues with parameters whose predicted magnitudes can be tested against experimental values.

The unique electronic structure results in one paramagnetic and one diamagnetic electron. The former induces a current in the latter by means of spin-orbit coupling resulting in a split of the original resonance into two lines separated by a frequency-independent interaction, which is for $H_2(1/4)$ predicted to be of magnitude 3.9943 gauss with the field center of the two lines corresponding to the original g value of 2.00464 [92]. Experimentally we observe two lines of equal intensity separated by 3.9 gauss whose center is found at g = 2.0045(6).

Linkage of magnetic flux by the electron is quantized in units of the magnetic flux quantum $\varphi_o = h/2e$, which results in a sub-line pattern of each of the two main lines with a predicted separation of 0.311 gauss [92]. The observed separation is 0.32 gauss.

Similar to the case of excited-states of the regular H_2 molecule, the two electrons in $H_2(1/4)$ may rotate relative to each other along the semimajor axis during a spin transition. The relative rotation is quantized in terms of m integer units of ħ in opposite directions with the spin-orbit splitting in frequency-independent field units equal to ± m times twice the splitting between the two main lines, that is ±m × 7.9885 gauss. Additionally, the unpaired electron must link the magnetic flux component corresponding to spin-orbit coupling. This flux contribution increases the magnetic energy and the energy of the combined spin flip and spin-orbit coupling transition energy for a given spin-orbital quantum number m. Thus the downfield spin-orbital splitting peaks are shifted further downfield by the corresponding magnetic energies, whereas the upfield spin-orbital splitting peaks are not shifted since they correspond to emission of the spin-orbital coupling transition energies alone.

Furthermore, each of these satellite lines is split through the linkage of magnetic flux during a spin transition, and the exact solution of the splitting is circa 0.62 gauss for $|m| = 1$ and circa 0.93 for $|m| > 1$ where the latter lines follow an intensity pattern $I_{m+1}/I_m = m/(m+2)$. The predicted details [92] of this complex pattern of split satellite lines asymmetrically grouped around a g value of 2.00464 make up a stick spectrum that, when convoluted with a Gaussian derivative, forms a semi-quantitative reproduction of the experimental spectroscopy (Fig. 4b and Table I).

Table I. Comparison of experimental and theoretical EPR peak positions of molecular hydrino. The experimental magnetic-field values are taken from the spectrum at 9.82029 GHz (Fig. 4a) as peak positions of the center line of 11 multiplets. The theoretical values [92] are due to the electron spin-orbit coupling splitting energies for downfield and upfield spin-orbit coupling quantum numbers m = 0, 0.5, 1, 2, 3, 4. All values are in gauss.

m	experimental	theoretical	difference
4	3480.5	3481.24	−0.74
3	3486.8	3486.50	0.30
2	3491.7	3491.39	0.31
1	3495.7	3495.93	−0.23
0.5	3498.5	3498.06	−0.44
0	3500.4	3500.10	0.30
0.5	3502.3	3502.10	0.20
1	3504.0	3504.09	−0.09
2	3507.8	3508.09	−0.29
3	3511.5	3512.08	−0.58
4	3517.3	3516.08	1.22
Average (st. dev.):	−0.004 ± 0.550		

Checks on consistency of EPR interpretation

Unequivocal interpretation of complex EPR spectra typically requires analysis of data taken at more than one microwave frequency. The magnetic model of molecular hydrino $H_2(1/4)$, providing a basis for interpretation of the EPR, predicts a number of features to be either dependent or independent of microwave frequency. These predictions can be checked in separate experiments as consistency tests. The g value of 2.00464 in between the two main lines is a real g value and thus its field position should be linear in the microwave frequency. Contrarily, all fine structure splittings are predicted to be constant in field units and thus independent of the frequency.

As a check we have taken data in Q-band at circa 35 GHz. Here, practical complications arise resulting in reduced signal-to-noise ratios. For S = 1/2 systems, any spectrometer operating in a frequency band different from X-band is generally found to exhibit a significantly lower concentration sensitivity. Furthermore, the maximal applicable intensity of the microwave is found to be limited (that is, the spectrometer is not tunable at higher microwave powers) apparently due to a relatively high dielectric permittivity of the Ga(O)OH samples.

Fig. 5 shows two traces resulting from extensive averaging, one taken under over-modulating conditions to emphasize the main two-line pattern, and one taken at lower modulation amplitude in an attempt to resolve fine structure. Consistent with the interpretation of the X-band spectrum we find a doublet of lines whose spectral center has a real g value of 2.0046 and with a frequency-independent splitting of circa 4 gauss. Under the employed conditions, the underlying broad signal has turned dispersive and thus shows up as an absorption-shape feature. A lower modulation amplitude does not afford resolution of the two-lines' fluxonal fine structure, which indicates that the spectral line width has increased with frequency. This is in fact consistent with our previous conclusion (cf. Fig 2c and Fig. S7) that the line shape is Gaussian due to inhomogeneous broadening, which implies a line width in field units linear in frequency [99].

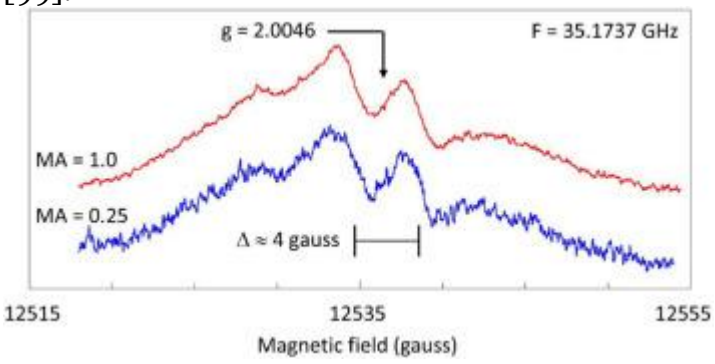


Fig. 5. A 35 GHz frequency experiment as check on consistency of the EPR interpretation: extensively averaged Q-band spectra taken at two different modulation amplitudes (MA) of 1 gauss (red) or 250 mG (blue). No fine structure is resolved in addition to the two main lines consistent with an inhomogeneous line width linear in the microwave frequency. The central g value and the splitting between the two lines in

field units are identical to those observed in X-band. See ESI for other experimental conditions.

Since the signal-to-noise ratio in Q-band was insufficient to detect the satellite lines, and since attempts to measure the samples in other frequency bands were hitherto unsuccessful (not shown), we took data at two, well-separated frequencies within the X-band thus allowing for comparison of high-resolution spectra with the trade-off of reduced frequency resolution (Fig. 6ab). Data taken at 9.46 GHz were transformed for comparison with data taken at 9.85 GHz in two ways: (1) frequency-ratio conversion of every digital point of the field axis, and (2) single-valued overall field shift to create maximal overlap of the two spectra. In the first method all real g values will overlay while features constant in the field will mismatch. In the second method all features of a fine-structure pattern constant in the field will overlay when the selected field point of conversion corresponds to the g value of that pattern. Fig. 6a gives the result of the first method: all features mismatch except for the spectral center at g = 2.0046, therefore the latter is the only real g value and all other features are from frequency-independent hyperfine interactions. Fig. 6b gives the result of the second method: all lines match, including all satellite lines and all fluxon sub-lines of the two main lines, therefore all features are from frequency-independent hyperfine interactions and they all share a single, common g value.

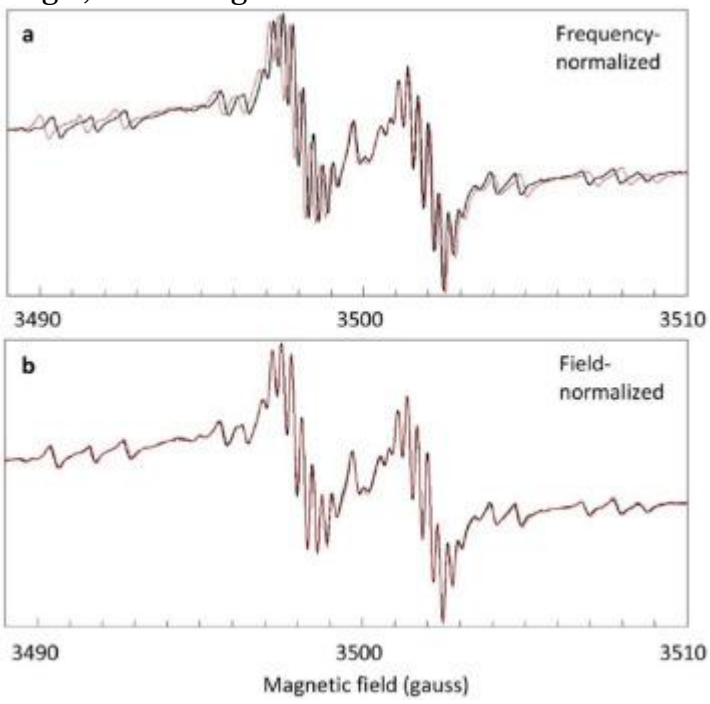


Fig. 6. In-band dual frequency experiment as check on consistency of the EPR interpretation. Trace a: extensively averaged intra X-band experiment at two frequencies, 9.4629 GHz (red) and 9.8209 GHz (black). Each field point of the red spectrum is frequency transformed to that of the black spectrum where the overlay shows that only the center of the two main lines is a real g value. In trace b the red spectrum is shifted in its entirety to a higher field for maximal overlap with the black

spectrum. Here the overlay proves that there is only a single real g value and that all other features are constant in the field.

Search for alternative interpretation of the EPR

Alternative to the hydrino analysis in Fig. 4b the spectrum in Fig. 4a can also be approximately reproduced under a conventional phenomenological spin Hamiltonian assuming an unusual combination of two isotropic radicals of unequal intensity each with a g value of 2.0046. This model would require the two main lines to be due to an isotropic S = 1/2 system split by an I = 1/2 nucleus with $A_{iso} \approx 3.9$ gauss with additional hyperfine structure form a combination of some five nuclei the majority of which has also I = 1/2. A second S = 1/2 system should give rise to the satellite lines due to a different combination of five nuclei, one of which should have I = 1 (e.g. ^{14}N) to account for the repeating triplet pattern (see Fig. S8 for a detailed analysis).

In addition to the improbability of the above combination of spin Hamiltonian parameters we consider this alternative explanation of the EPR highly unlikely on the following grounds. The reaction mixture only contains H_2, O_2, H_2O, and Ga. Even in the presence of trace contaminants we cannot envision how the high-temperature plasma reaction conditions and sample formation in strong aqueous base could lead to the formation of stable radical structures of considerable complexity. The ToF-SIMs, EDS, and XRD analyses also eliminate alternatives. Furthermore, since the sample is a solid, for complex radicals one would expect to see anisotropy in the spectra. In particular absorption-shaped peaks that come with axial or rhombic symmetry of the spin Hamiltonian are not observed. Finally, when the sample temperature is lowered below ambient, relaxation of the two main peaks becomes distinct (Fig. S9), which would be hard to reconcile with a nuclear hyperfine doublet assignment.

Remaining questions

The GUTCP fit to the X-band spectrum of $H_2(1/4)$ is semi-quantitative with an average error of 0.004 ± 0.550 gauss over the 11 lines assigned to spin-orbital coupling splitting. The actual positions of the satellite lines slightly deviate from their predicted values (Fig. 4a, b and Table I). Also, the fluxon separation for any given position does not quantitatively fit the predicted value; in particular the separation is not a constant. Also, the number and relative intensities of fluxon lines for a given satellite line are presently not understood. Possibly these small irregularities are caused by interactions of the gaseous $H_2(1/4)$ with the wall of the polymeric Ga(O)OH microspheres.

A broad signal underlies the molecular-hydrino assigned spectrum. Its spectral center corresponds to the g value of 2.0046 within experimental error. Its temperature behavior is very different from that of the hydrino-assigned spectrum (Fig. S10). The origin and nature of the broad signal are presently unknown, however, a reasonable hypothesis would be to assume that there are two phases of Ga(O)OH that encapsulate $H_2(1/4)$ wherein $H_2(1/4)$ is a near free gas in only one phase. A scanning/transmission electron microscope (SEM/TEM) used for imaging and selected area electron diffraction (SAED) (Fig. S3) showed that the $H_2(1/4)$@Ga(O)OH sample comprised two different morphologically polymeric crystals of Ga(O)OH, a hexagonal crystalline structure that

was very sensitive to the TEM electron beam, and rods having orthorhombic crystalline structure that were not electron beam sensitive. The rod crystal morphology and crystalline structure match those of the literature for control Ga(O)OH that lacks gaseous molecular hydrino inclusion [91]. The XRD crystal system for tsumgallite (control Ga(O)OH) is orthorhombic. The hexagonal phase is likely the source of the fine structure EPR spectrum, and the orthorhombic phase is likely the source of the broad background EPR feature. Cooling selectively eliminates, by microwave power saturation, the observed near free-gas-like EPR spectral behavior of $H_2(1/4)$ trapped in the hexagonal crystalline matrix. In addition to wall interactions, deviations from theory could be due to the influence of the proton of Ga(O)OH and those of absorbed water. Also, matrix orientation in the magnetic field, matrix interactions, and interactions between one or more $H_2(1/4)$ could cause some shifts.

Deuterium substitution was performed to eliminate an alternative assignment of any EPR spectral lines as being nuclear split lines. Rotational-nuclear interaction was predicted to be absent since the experimentally confirmed theoretical rotation energy of $H_2(1/4)$ is 16 times that of H_2, too high to be excited at ambient temperatures [12,13]. The EPR spectrum of the deuterated analog HD(1/4)@Ga(O)OH showed a singlet with no fine structure (Fig S11); thus, eliminating any possible nuclear splitting assignment. The g factor and profile matched that of the singlet of $H_2(1/4)$@Ga(O)OH wherein the singlet in both cases was assigned to the orthorhombic phase. The XRD of the deuterated analog matched that of the hydrogen analog, both comprising gallium oxyhydroxide. TEM confirmed that the deuterated analog comprised 100% orthorhombic phase [91]. The phase preference of the deuterated analog may be due to a different hydrino concentration and kinetic isotope effect which could have also reduced the concentration.

Conclusions

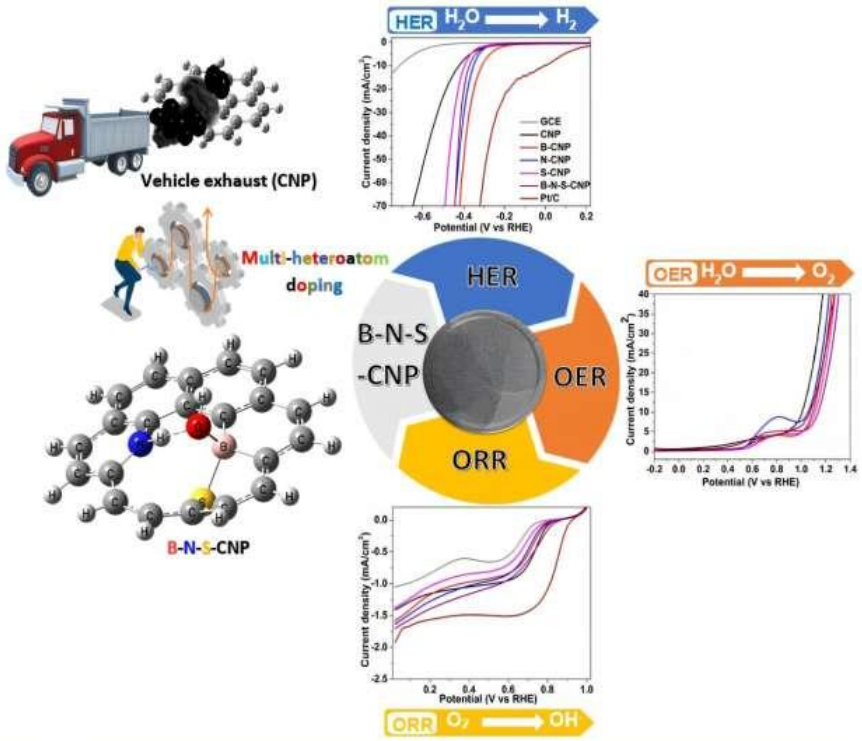
A plasma reaction has been carried out intended to produce molecular hydrino using non hydrogen bonded water as the catalyst and with liquid gallium as one of the electrodes. Polymeric Ga(O)OH with a spherical particle structure, presumably containing $H_2(1/4)$, was purified from the reaction mixture. $H_2(1/4)$ is proposed to be an S = 1/2 paramagnet with complex fluxonal and spin-orbital coupling sub-level structure. The solid Ga(O)OH compound exhibits a complex gas-phase X-band EPR spectrum at ambient temperature whose fine structure semi-quantitatively agrees with hydrino-theory predictions. This analysis is consistent with frequency-dependent studies, while alternative, conventional interpretations are judged to be extremely unlikely. In summary, the present study provides compelling EPR spectroscopic and gas chromatographic evidence for the existence of molecular hydrino, and, by inference, for the reality of atomic hydrino, and it provides plausibility of the electron model in GUTCP. In more general terms our results are a significant test against falsification of GUTCP. In view of the possible far-reaching implications of this conclusion for the theory of quantum mechanics, for hydrogen-related chemistry, for astrophysics of dark matter, and for energy transduction and production technology, it is also offered as an urgent invitation to academia at large to repeat and extend the described experiments in

lieu of refutation on quantum mechanical theoretical grounds. An early version of the present paper has been posted on a preprint server [100].

MARCH 3, 2025

Turning pollution into power: New method transforms carbon nanoparticles from emissions into renewable energy catalysts

by Shiv Singh



Research in a nutshell. Credit: *Carbon Neutralization* (2025). DOI: 10.1002/cnl2.195

We have developed a breakthrough method to convert carbon nanoparticles (CNPs) from vehicular emissions into high-performance electrocatalysts. This innovation provides a sustainable approach to pollution management and energy production by repurposing harmful particulate matter into valuable materials for renewable energy applications.

Our work, published in *Carbon Neutralization*, addresses both environmental challenges and the growing demand for efficient, cost-effective clean energy solutions.

Advancing electrocatalysis with multi heteroatom-doped CNPs

By doping CNPs with boron, nitrogen, oxygen and sulfur, we have significantly enhanced their catalytic performance. These multiheteroatom-doped nanoparticles exhibit remarkable efficiency in key electrochemical reactions. Our catalysts demonstrate high activity in the oxygen reduction reaction (ORR), which is essential for fuel cells and energy storage systems, as well as in the hydrogen evolution reaction (HER), a crucial process for hydrogen fuel production.

Additionally, they show superior performance in the oxygen evolution reaction (OER), advancing water splitting for green hydrogen generation. By optimizing the composition of these materials, we have created an effective alternative to conventional precious metal-based catalysts, improving both cost-efficiency and sustainability.

Scientific insights and performance metrics

Using a combination of experimental analysis and density functional theory (DFT) modeling, we have gained deeper insights into the structural and electronic properties of these doped CNPs. Our boron-doped CNPs demonstrated an overpotential of 338 mV at 10 mA/cm², while B-N-S-CNPs exhibited a Tafel slope of 83.09 mV/dec, indicating superior reaction kinetics.

High-resolution TEM imaging revealed a sponge-like fractal structure, which enhances charge transfer and increases the number of active reaction sites. Raman spectroscopy confirmed increased disorder in heteroatom-doped CNPs, generating additional active sites for energy conversion.

Furthermore, modifications to the surface chemistry disrupted electroneutrality, improving adsorption and reaction efficiency and resulting in a more robust catalytic system. These material advancements allow us to reduce reliance on costly platinum-based catalysts, making clean energy technologies more viable and accessible.

Industrial applications and future prospects

Our research has far-reaching implications for clean energy and sustainable transportation industries. These catalysts can be integrated into fuel cells, enabling more efficient power generation for electric vehicles and energy storage systems. They also play a vital role in hydrogen production, supporting the transition to a hydrogen-based economy. Additionally, their use in renewable energy storage systems enhances the stability of wind and solar power generation.

While our findings demonstrate significant promise, further research is needed to scale up production, optimize material stability, and integrate these catalysts into commercial applications. Overcoming challenges related to large-scale synthesis and ensuring long-term durability will require collaboration between scientists, industries, and policymakers.

By refining manufacturing processes and developing sustainable extraction methods, we can transform pollution into a valuable energy resource, supporting the transition to a circular economy. With continued advancements, we can turn vehicular emissions from an environmental burden into a solution for clean and sustainable energy.

This story is part of Science X Dialog, where researchers can report findings from their published research articles. Visit this page for information about Science X Dialog and how to participate.

More information: Manish Chauhan et al, Trifunctional Nature of Heteroatom (B, N, S, O)-Doped Waste Diesel Soot: Turning Pollutants Into Potential Energy Catalysts for HER, OER, and ORR, *Carbon Neutralization* (2025). DOI: 10.1002/cnl2.195

Bio:

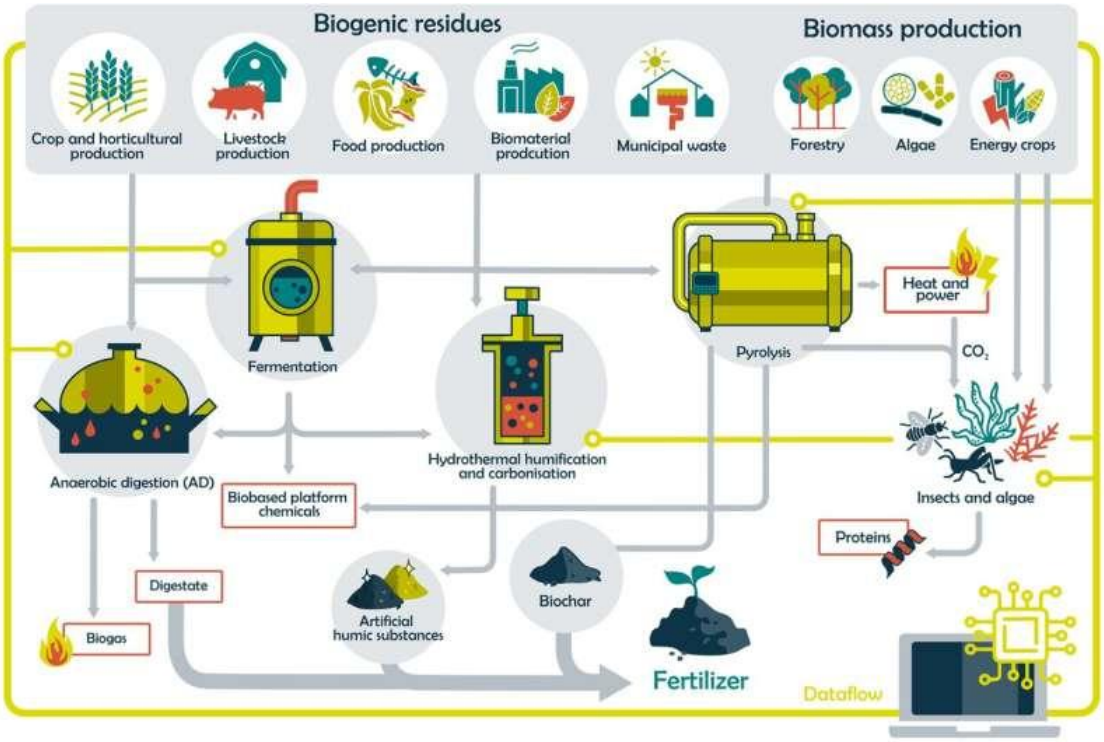
Dr. Shiv Singh, Sr. Scientist at CSIR-AMPRI, Bhopal, specializes in carbon-based nanomaterials for energy, electrochemical sensors, CO_2 reduction, and environmental remediation. His work focuses on waste-to-wealth applications, including microbial fuel cells (MFCs), advanced electrodes, and bioelectrochemical systems. With 50 publications (2,600 citations, h-index: 31, i10-index: 48, Avg IF ~8), he has developed cost-effective electrodes from vehicle and candle exhaust-derived carbon nano-onions. His innovations in CO_2 electro-reduction and photocatalysis have led to impactful solutions. He was recognized with the Marie Skłodowska-Curie Seal of Excellence, DST INSPIRE Faculty Award, and listed among Stanford's Top 2% Scientists (2023). He has also been selected to join the RSC *Materials Horizons* journal's Community Board and serve as a Young Editorial Board member for the *Nano-Micro Letters* journal published by Springer, Wiley's *Energy & Environmental Materials* and *Scientific Reports*.

Journal information: Scientific Reports , Materials Horizons

MARCH 3, 2025

High value, zero waste: Researchers conceptualize novel biorefinery

by Jessica Lietze, Leibniz-Institut für Agrartechnik und Bioökonomie e.V. (ATB)



Overview of the smart integrated biorefinery concept. Credit: *Biofuel Research Journal* (2025). DOI: 10.18331/BRJ2025.12.1.4

What does it mean if our economy works without fossil raw materials such as oil and gas? The logical answer is that we will have to create value almost exclusively with biological, renewable resources. This so-called bioeconomy presents us with major challenges, both locally and globally.

Researchers from Leibniz Institute for Agricultural Engineering and Bioeconomy in Potsdam recently published a concept paper in the *Biofuel Research Journal*, which combines common bioeconomy models into a comprehensive concept. They describe what a circular and sustainable bioeconomy within planetary boundaries could look like. Smart integrated biorefineries are a key component of this vision.

Biomass, i.e. grown, biological raw materials, are a great treasure. We eat it, feed it, burn it or utilize it. What remains is usually composted, landfilled or incinerated. Yet there is still potential in every unused residue. One way to utilize this potential is through intelligent, integrated biorefineries. Unlike conventional biorefineries, in which chemical companies, for

example, extract one special biochemical from one special biological starting material, they combine several conversion processes.

The potential of intelligent biorefineries is immense

Dr. Nader Marzban is a researcher at Leibniz Institute for Agricultural Engineering and Bioeconomy (ATB) and lead author of the conceptual paper "Smart Integrated Biorefineries in Bioeconomy: A Concept Toward Zero-Waste, Emission Reduction, and Self-Sufficient Energy Production." He describes it like this: "There are many conversion technologies that generate valuable materials from biomass. These include, among others, microbial fermentation, such as anaerobic digestion, and pyrolysis. Anaerobic digestion, for example, produces biogas, whereby the remaining digestate still contains valuable organic compounds.

"Instead of using it as a fertilizer, as is traditionally the case, we can convert this digestate into artificial humic substances through hydrothermal humification. When introduced into the soil, it stabilizes bacterial diversity and improves soil health. Another promising approach is the combination of anaerobic fermentation with pyrolysis, i.e. carbonization.

"Here, biochar acts as a catalyst and increases the efficiency of biogas production. At the same time, the biochar is enriched with nutrients. It can thus keep nutrients available in the soil for a long time and—depending on the process conditions—store carbon for more than a century.

"Another example is fermentation. If biochar is added, fermentation inhibitors are broken down, which significantly increases the ethanol and lactic acid yield. In addition, the bioheat and electricity generated during pyrolysis can be used for fermentation, which reduces dependence on external energy sources. CO_2 emissions from pyrolysis can be captured and used for the cultivation of algae, which in turn serve as an alternative source of protein."

The potential of intelligent biorefineries is immense, but so is the number of possible optimizations. Industrial processes such as anaerobic digestion, fermentation, pyrolysis, carbonization and humification each have adjustable parameters and can be combined in a variety of ways. Instead of relying on a single type of biomass, the researchers work with 90 different raw materials that vary regionally and seasonally. By defining key objectives and adjustable parameters for each process, millions of potential scenarios are created.

Dr. Marzban points out, "Investigating all these scenarios experimentally would be extremely costly and time-consuming. Yet time is a luxury that we cannot afford. Our economy is still heavily dependent on fossil raw materials. We are already seeing the negative effects. That's why we rely on AI-driven simulations to identify the most efficient approaches. As process scientists, we proceed step by step and initially optimize subsystems, which we then gradually link together to combine them into a larger whole."

A sustainable bioeconomy with zero waste and within planetary boundaries

Global industry expertise and extensive research results—including from ATB—provide a rich data basis for the further development of existing biomass conversion processes. Key technologies are sensors that measure directly in the processes and help to gain a better understanding of product-process interactions as well as artificial intelligence, digital twins and advanced modeling techniques. By leveraging data, processing capacities and algorithms, smart integrated biorefineries can be developed that are adaptable and scalable and can process thousands, if not millions, of scenarios.

Prof Barbara Sturm, Scientific Director at ATB and corresponding author of the paper explains, "The smart integrated biorefineries can be developed using networks and dialogues between different modeled systems and then be validated in reality. This validation process allows for the identification of gaps and the uncovering of hidden opportunities, which can be addressed either by repurposing existing technologies and systems or by introducing innovative solutions such as artificial humic substances.

"In this systemic approach, each biorefinery component actively seeks connections with others, forming larger, integrated networks. This system would constantly simulate the next steps to find out the best way to achieve defined goals. That will enhance sustainability and circularity within bioeconomic models, creating jobs and supporting the policy maker. Our vision is to achieve a more resilient, efficient and future-proof bio-based economy through this systemic integration."

The integrated approach could enable us to create a truly sustainable bioeconomy with zero waste and remaining within our planetary boundaries. It increases profitability and competitiveness, which is urgently needed given the lower cost of fossil products. Nevertheless, government support and policy interventions are crucial to facilitate and accelerate the transition to green technologies.

In the long term, smart integrated biorefineries will undoubtedly be more profitable than systems focused on a single process. They will also reduce the need to import raw materials and thus increase the resilience of our economic systems.

Time for implementation

With the concept paper, the ATB team together with partners from the University of Potsdam and the Technical University of Berlin has taken the first step. Now it's time for proving and implementation.

This March, ATB will begin construction of a biorefinery for research purposes in Groß Kreutz, Brandenburg, Germany. This will complement the existing pilot plants and facilities at the Potsdam site and the Fieldlab for Digital Agriculture in Potsdam-Marquardt. As part of the Leibniz Innovation Farm for Sustainable Bioeconomy (InnoHof), a facility is being

created that will not only bring together research and practice in a co-creative way, but will also demonstrate the feasibility of such concepts.

Furthermore, ATB is in the process of applying for an extension of the institute in order to integrate such systemic approaches even more consistently into its research. In a joint appointment with the University of Osnabrück, ATB is currently filling a professorship for systems science in bioeconomy.

Prof. Sturm emphasizes, "We have to think about systemic, technical, social and economic innovations together. Only if we understand a system as a whole will we be able to optimize subsystems in such a way that they effectively serve sustainability. With our concept, we will further intensify interdisciplinary bioeconomy research with political decision-makers, industry leaders and the food and nutrition sector with the aim of increasing the resilience of our economic system, making our economy more sustainable and supporting the technological sovereignty of Germany and Europe."

More information: Nader Marzban et al, Smart integrated biorefineries in bioeconomy: A concept toward zero-waste, emission reduction, and self-sufficient energy production, *Biofuel Research Journal* (2025). DOI: 10.18331/BRJ2025.12.1.4
Provided by Leibniz-Institut für Agrartechnik und Bioökonomie e.V. (ATB)

Breakthrough 6G antenna could lead to high-speed communications and holograms

published May 2, 2024

Scientists build the world's first 6G antenna that, when fitted into devices, can transmit data at high speeds.

A new programmable antenna is the world's first to work with a 6G signal in the 60 GHz millimeter-wave (mmWave) band. (Image credit: Design_Cells via Shutterstock)

A new programmable antenna could pave the way for a new generation of 6G devices, smart city-type applications and 3D holograms, scientists claim.

Researchers have created a dynamic metasurface antenna (DMA) that could be controlled by a digitally coded miniature processor that is technically, a high-speed field programmable gate array (FPGA) — a type of reconfigurable circuit integrated onto a chip.

This prototype, which is about the size of a matchbox, is the world's first to work with a 6G signal in the 60 GHz millimeter-wave (mmWave) band — reserved for industrial, scientific and medical applications. The findings are detailed in a new study accepted for publication in the near future in the journal IEEE Open Journal of Antennas and Propagation.

The most advanced mobile communications standard today is 5G. This network was first established in 2018 before becoming widespread in 2019. Today, almost every new smartphone can connect to 5G networks in the U.S. and globally.
6G — which could be a thousand times faster than 5G — is next in line, with the technical specifications still being decided, alongside the infrastructure and components needed to make this network a reality. The final specifications for 6G are expected in 2028, with commercial rollout likely to follow in the early 2030s, according to the trade body GSMA.
Related: Breakthrough photonic chip could power 6G devices
"Our high-frequency intelligent and highly adaptive antenna design could be one of the technological foundation stones of the next generation of mmWave reconfigurable antennas," said lead author of the research, Masood Ur Rehman, senior lecturer in autonomous systems and connectivity at the University of Glasgow, in Scotland, in a statement.
One of the prototype antenna's key features is beamforming. This focuses the direction of the 6G signal precisely to the target device, which increases reliability and speed while reducing power demands. This process happens in nanoseconds. Here, the researchers used "metamaterial" elements designed to resonate at around 60.5 GHz that can be fine-tuned without the need for complex circuitry.

"The programmable beam control and beam-shaping of the DMA could help in fine-grained mmWave holographic imaging as well as next-generation near-field communication, beam focusing, and wireless power transfer," said Ur Rehman.

In the study, the researchers said this device could have a major impact in communication, sensing and imaging.

One of the main challenges for 6G is that it is difficult to obtain a signal inside a building. This new antenna could support large-scale 60GHz indoor Internet of Things (IoT) networks that encompass high transmission rates and massive data throughput" the scientists said in their report. In tests, the prototype reduced energy consumption by 88% and data collisions by 24%, compared to omnidirectional antennas.

Sensing via 6G also raises interesting possibilities. This uses the properties of radio waves to detect objects in real-time, with potential applications including tracking patients in a

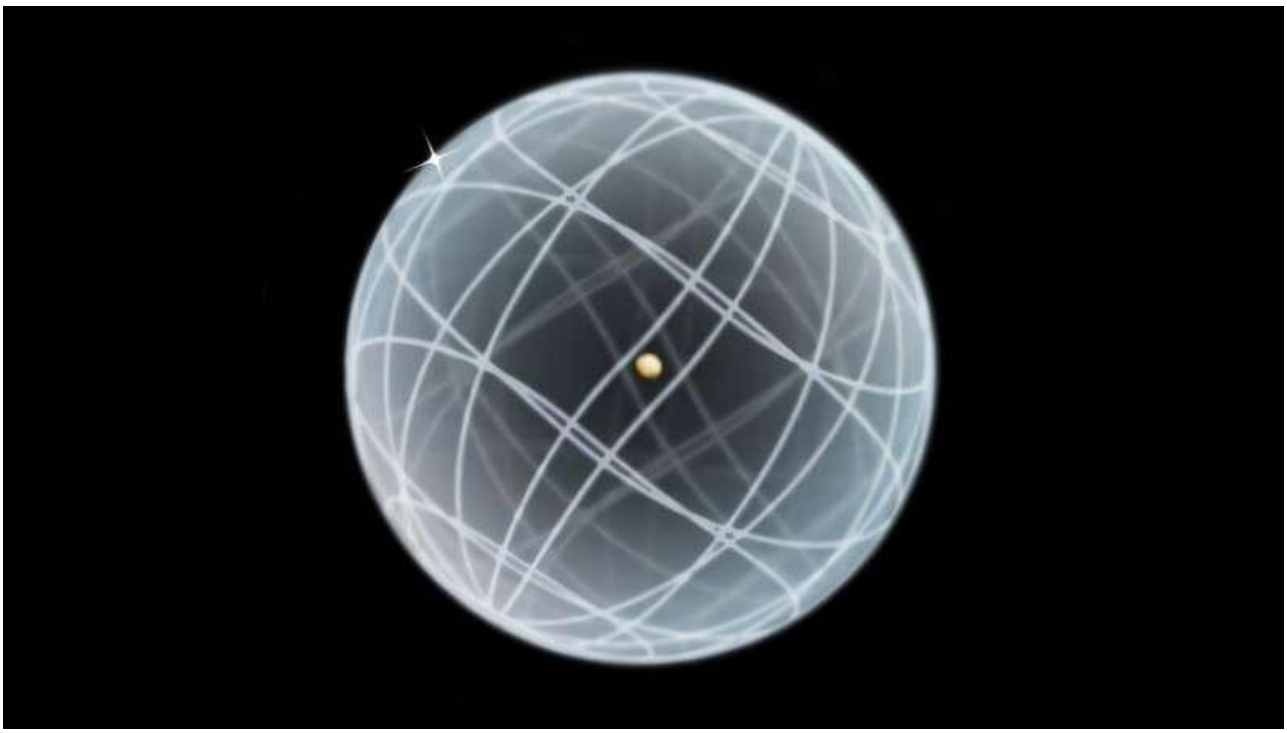
hospital or determining the path of an autonomous car. Using this captured data might also lead to the creation of 3D holographic models showing the movement of people and objects in the local area, the scientists said.

Ur-Rehman said his team is just at the start of the journey, and plans to improve the design so that the antenna offers greater flexibility and more versatile performance. Eventually, Ur Rehman sees it as a key component in 6G-enabled IoT and smart city environments.

MARCH 4, 2025

Collaborative analysis improves theoretical understanding of hyperfine splitting in hydrogen

by Chris Patrick, Thomas Jefferson National Accelerator Facility



A hydrogen atom contains a single proton in its nucleus with a single orbiting electron. Credit: DOE's Jefferson Lab

Two experiment collaborations, the g2p and EG4 collaborations, combined their complementary data on the proton's inner structure to improve calculations of a phenomenon in atomic physics known as the hyperfine splitting of hydrogen. An atom of hydrogen is made up of an electron orbiting a proton.

The overall energy level of hydrogen depends on the spin orientation of the proton and electron. If one is up and one is down, the atom will be in its lowest energy state. But if the

spins of these particles are the same, the energy level of the atom will increase by a small, or hyperfine, amount. These spin-born differences in the energy level of an atom are known as hyperfine splitting.

While it's commonplace for many scientists to collaborate on nuclear physics experiments at the U.S. Department of Energy's Thomas Jefferson National Accelerator Facility, it's rarer for the lab's individual experiments to collaborate with each other. But that's exactly what g2p in Jefferson Lab's Experimental Hall A and EG4 in Experimental Hall B did.

The two collaborations combined their complementary data on the proton's inner structure to improve calculations of a phenomenon in atomic physics: the hyperfine splitting of hydrogen.

An atom of hydrogen, the simplest and most abundant element in the universe, is made up of an electron orbiting a proton. Both of these particles have a property known as angular momentum, commonly known as spin, which can be oriented "up" or "down."

The overall energy level of hydrogen depends on the spin orientation of the proton and electron. If one is up and one is down, the atom will be in its lowest energy state, like two dipole magnets that want to be anti-aligned. On the other hand, if the spins of these particles are the same, the energy level of the atom will increase by a small, or hyperfine, amount. These spin-born differences in the energy level of an atom are known as hyperfine splitting.

Since the discovery of hyperfine splitting in the 1930s, scientists have measured this energy difference in hydrogen very precisely. However, theory hasn't been able to keep up.

"Our theoretical understanding of it is a million times worse than our experimental measurement of it," said David Ruth, a postdoctoral associate at the University of New Hampshire. "Different things contribute to that, but what dominates our uncertainty in the calculations is a lack of understanding of the internal structure of the proton."

Fortunately, g2p and EG4 happened to probe exactly that.

Greater than the sum of their parts

Ultimately, hyperfine splitting in hydrogen is caused by the interaction of the proton and the electron. Unlike the electron, the proton is not a fundamental particle: it's made up of smaller particles called quarks and gluons. As a result, precise calculations of hyperfine splitting need to include information about the proton's internal structure. But the inside of the proton is complicated and not fully understood, making it difficult to describe with theory alone.

The g2p and EG4 experiments were both designed to study how the proton's constituent quarks make up its overall spin. To do so, these experiments aimed the electron beam generated in the Continuous Electron Beam Accelerator Facility (CEBAF), a DOE

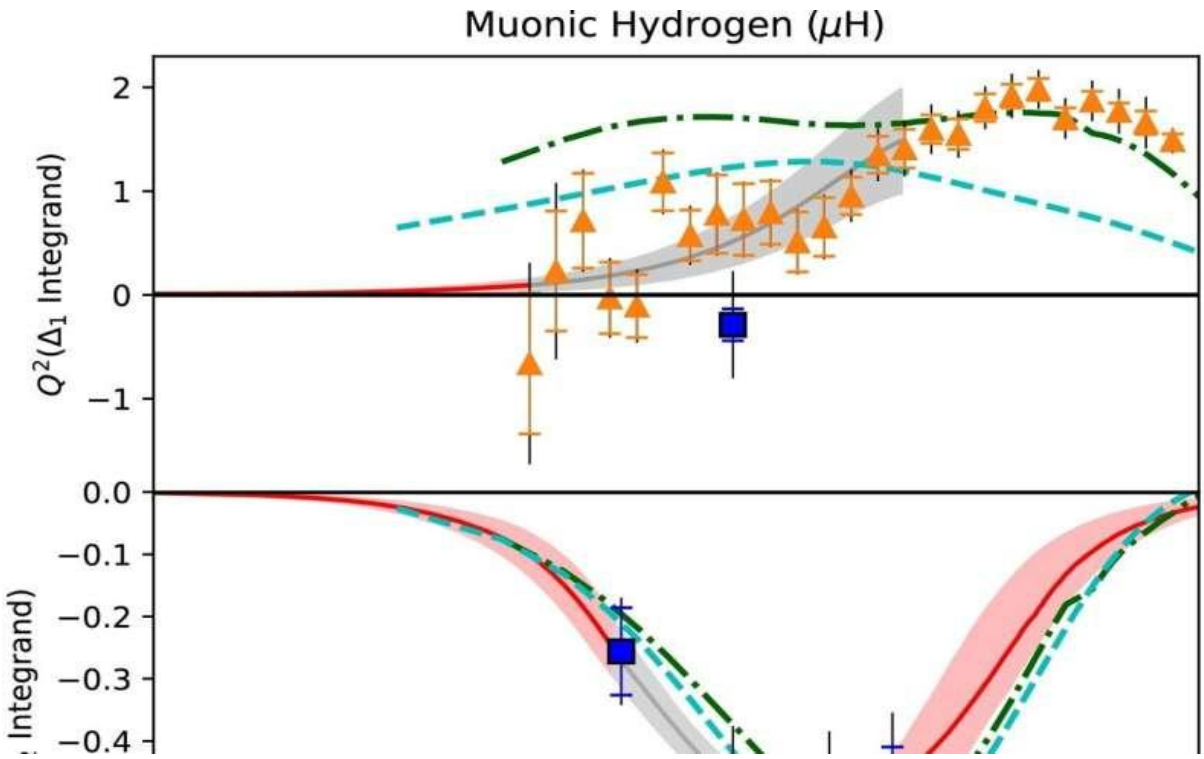
Office of Science user facility, at a polarized proton target—a target of protons whose spins are all oriented in the same direction.

In g2p, the proton target was transversely polarized, or the spins were oriented perpendicular to the electron beam. In EG4, the proton target was longitudinally polarized, or the spins were oriented parallel to the electron beam.

Detecting the beam electrons, which were also polarized, after they interacted with the polarized targets allowed these experiments to measure different aspects of the proton's spin structure.

"We collected this data for our own purpose, to learn more about the internal structure of the proton and test theories related to the proton, but we produced the same data needed for better understanding hyperfine splitting," said Alexandre Deur, a staff scientist at Jefferson Lab who worked on EG4. "It was a stroke of good luck."

In a paper published in *Physics Letters B*, experimentalists from g2p and EG4 applied their distinct but compatible proton spin structure data to calculations of hyperfine splitting in hydrogen.



The hyperfine contribution integrands for Δ_1 and Δ_2 in Eqs. (5) and (6), weighted by Q^2, for muonic hydrogen. Results from the g2p experiment [23] are shown in blue squares. The results of the EG4 experiment [24] are shown in orange triangles. The inner error bars represent the statistical uncertainty, while the outer error bars represent the total uncertainty including systematic error. The green dash-dot and cyan dashed lines represent the phenomenological Hall B and MAID models [25], [26] respectively. The form factor term of the integrand for Δ_1 is constructed using the Arrington form factor fit [27]. The red line

indicates a new phenomenological fit to the data and extrapolation to low $Q^2=0$ and high Q^2, with the red band representing the uncertainty of the calculation. The results are similar but have different mass scaling in electronic hydrogen. Credit: *Physics Letters B* (2024). DOI: 10.1016/j.physletb.2024.139116
This cut the uncertainty related to proton structure in hyperfine splitting calculations in half, advancing theoretical understanding of this effect and atomic structure in general.

"The g2p and EG4 experiments were two gargantuan efforts, but, independently, neither of them could have answered this question," said Karl Slifer, professor of physics at the University of New Hampshire who worked on g2p. "Together, the data were the perfect complement. This paper is the distillation of countless hours and hundreds of people's efforts."

In addition to bridging Jefferson Lab's experimental halls, this work connected fields.

The experimentalists of g2p and EG4 worked closely with Carl Carlson, Franziska Hagelstein and Vladimir Pascalutsa, nuclear theorists knowledgeable in atomic physics, who ensured the calculations were as precise as possible.

"During every step of this analysis, we were having a back-and-forth conversation with the theorists," said Ruth, who worked on the g2p experiment as a graduate student. "I think the result is pretty cool because it's a lot more of a direct collaboration between experiment and theory than usual."

Over a year and a half, Ruth spearheaded the analysis and coordinated the meetings for this work.

"David did a great job," said Jian-Ping Chen, a principal staff scientist at Jefferson Lab who worked on the g2p experiment. "He got all the experimentalists and theorists together to discuss this work. It is because of his persistence that we got this result out."

The ultimate goal is for theorists in atomic physics to use these results to precisely and completely calculate hyperfine splitting of hydrogen from theory.

A muonic future

These hyperfine splitting calculations are also relevant to an exotic form of hydrogen called muonic hydrogen. In muonic hydrogen, the electron is replaced by a muon, which is 200 times heavier. This weight pulls the muon closer to the proton, where it is more sensitive to the proton's internal structure.

In 2010, atomic physicists at the Paul Scherrer Institute (PSI) in Switzerland measured the radius of a proton in muonic hydrogen and found it was smaller than previously thought. This unexpected discovery was dubbed the proton radius puzzle.

"That was a big surprise," Deur said. "And that came about simply because they started playing with muonic hydrogen."

An upcoming experiment at PSI will again probe muonic hydrogen, this time in an attempt to precisely measure its hyperfine splitting. The results of the new analysis from g2p and EG4 will help to guide this PSI measurement.

There are multiple ways to define the proton's radius. The measurement in the proton radius puzzle was of the proton's charge radius. In addition to carrying out calculations related to hyperfine splitting, the collaborators of this work used g2p and EG4's data to refine the value of the proton's Zemach radius, which is a combination of its charge radius and its magnetic radius. Previous measurements and theoretical calculations of this type of radius disagree, but the extracted value bridges this gap.

"This new extraction of the Zemach radius of the proton gives us a better understanding of the physical dimensions of the proton and its messy composite structure," Slifer said.

There's still more to learn about the proton. Future experiments at Jefferson Lab will further probe this particle's internal structure, and Chen hopes they also find use outside of nuclear physics.

"I'd like future experiments at Jefferson Lab to have more broad collaboration among different halls, with theorists, and even with other fields," Chen said. "It's important to go in all these directions to give the results as much impact as possible."

More information: David Ruth et al, New spin structure constraints on hyperfine splitting and proton Zemach radius, *Physics Letters B* (2024). DOI: 10.1016/j.physletb.2024.139116
Journal information: Physics Letters B
Provided by Thomas Jefferson National Accelerator Facility

US to test crucial nuclear ‘fusion blanket’ to produce sun-like power on Earth

INL is leading one of the centers in the FIRE collaborative, and contributing in research for two other centers.

Updated: Mar 11, 2025

Rendering of a part of the nuclear fusion blanket.

Scientists at the United States Idaho National Laboratory (INL) are carrying out tests for ‘fusion blanket’ technologies to create a critical component of the nuclear fusion reactor.

The work at INL is being carried out as part of the US Department of Energy’s (DOE) $107 million funding award to six research centers called Fusion Innovative Research Engine (FIRE) collaborative.

INL is leading one of the centers in the FIRE collaborative and contributing to research for two other centers. The aim is to develop an operational fuel cycle within a decade and innovate solutions for commercial nuclear fusion plants to secure a resilient, reliable energy source.

The INL-led center, Accelerating Fusion Blanket Development through Nuclear Testing (BNT), involves five national laboratories, four universities, and numerous private companies.

General Atomics, one of the US companies, is providing engineering and advanced computer models. Another firm, Tokamak Energy, is collaborating to develop and design the fusion blanket technology.

“Fusion blankets are pivotal to delivering limitless fusion energy to the grid,” said Aaron Washington, a Tokamak representative. “We’re now focused on helping INL and DOE ensure their testing is relevant to private companies as part of a fusion energy future.”

Nuclear fusion blanket and its relevance

Fusion happens when two of the smallest atoms are combined. It requires special hydrogen atoms called deuterium (which has one neutron) and tritium (which has two neutrons). Fusing them together generates a tremendous amount of energy, the same reaction that occurs inside the sun.

Chase Taylor, a senior scientist at INL who is leading irradiation testing in the collaborative, stated that a "fusion blanket is the nuclear part of a fusion reactor."

The fusion blanket's role is to capture the energy and particles produced during the fusion reaction.

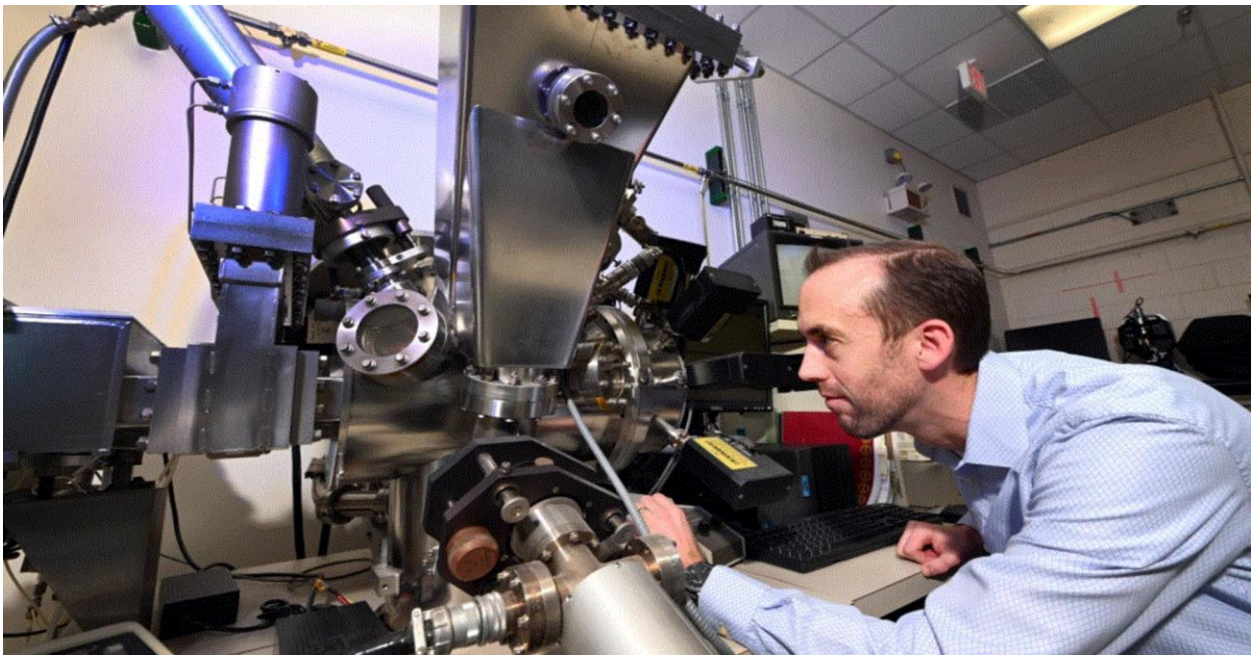
They serve three important purposes in a nuclear fusion plant – they create new fuel for the reactor, convert nuclear fusion power into heat for power generation, and they also protect the nuclear reactor's magnets.

INL to test nuclear fusion blankets in fission reactors

The ongoing research at INL had largely been focused on nuclear fission. Therefore, US scientists will use the existing capabilities to check the fusion blanket's performance in a nuclear setup.

The team will test portions of a blanket system in fission reactors, as per a release from INL.

One of the scientists associated with the project stated that this will help the "fusion energy industry by providing a way to test these materials in real-life conditions quickly."



Chase Taylor at the Safety and Tritium Applied Research (STAR) Facility. *INL*

"The lack of fusion neutrons (the particles produced by fusion reactors available for testing) has stalled progress in developing necessary technologies for fusion reactors," Taylor said.

“However, we can meet most of the fusion industry’s nuclear testing requirements using our nation’s leading fission research reactors.”

More work is being done by INL for FIRE collaborative

INL is also helping the team that has been charged with developing, designing, and manufacturing fusion energy materials.

INL also will provide modeling and simulation support for a Savannah River National Laboratory-led team tasked with enhancing fusion fuel-cycle technology development capabilities.

The fusion reactor needs special fuel to create energy like a car needs gasoline. The fusion fuel cycle is the process of making, using, and recycling that special fuel – which includes the hydrogen isotopes deuterium and tritium.

The challenges include making sure there’s enough tritium, handling the waste safely, and ensuring the reactor materials stay strong and efficient.

The INL scientists will use the MOOSE-based open-source modeling codes and the high-performance computing power of INL’s Bitterroot, Sawtooth, and Hoodoo supercomputers to contribute to these efforts.

“Establishing a robust fuel cycle is critical for commercial fusion energy production, but there are still significant challenges to address,” said Casey Icenhour, computational scientist.

“The collaborative intends to address these challenges through fuel cycle process modeling and cutting-edge technology development. They’ll also seek solutions for handling byproduct materials and growing the fuel cycle workforce of the future.”

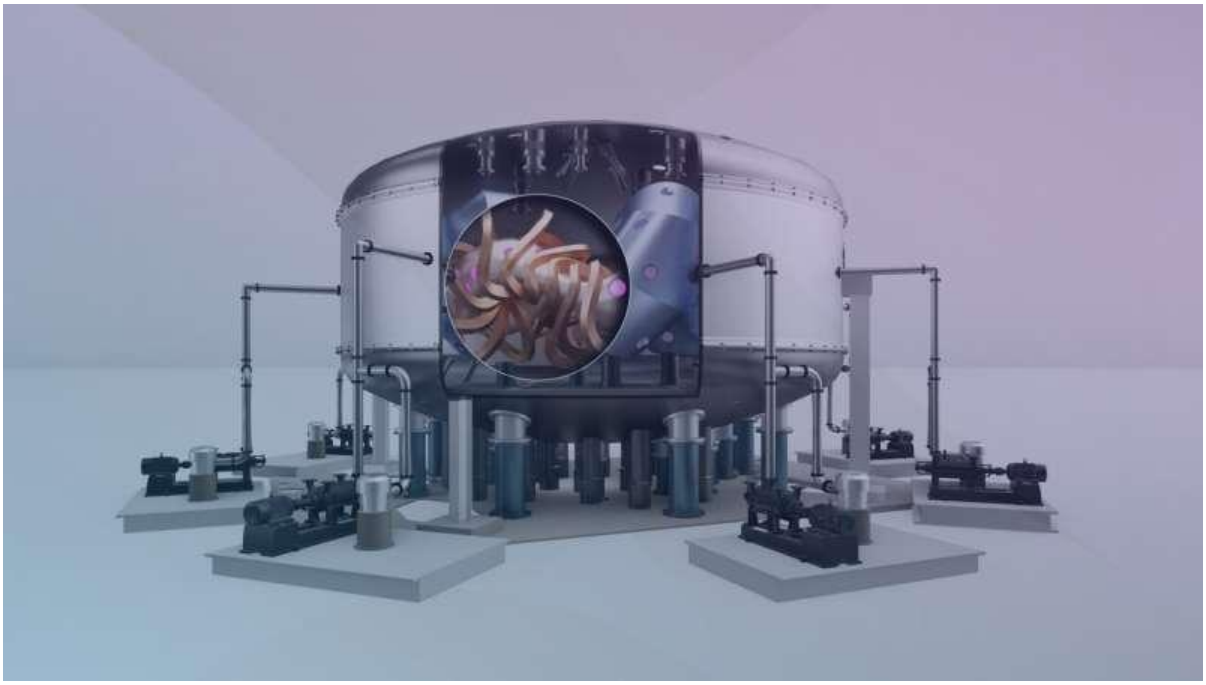
Fusion energy start-up companies are pushing for faster development timelines, which has changed the dynamic of the conversation around fusion energy.

The Nuclear Regulatory Commission will not regulate fusion reactors like fission reactors which reduces the regulatory requirements for fusion reactor licensees

MARCH 28, 2025

Commercial fusion power plant now closer to reality

by Cambridge University Press



Credit: Type One Energy.

Successfully harnessing the power of fusion energy could lead to cleaner and safer energy for all—and contribute substantially to combating the climate crisis. Towards this goal, Type One Energy has published a comprehensive, self-consistent, and robust physics basis for a practical fusion pilot power plant.

This groundbreaking research is presented in a series of six papers in the *Journal of Plasma Physics* (*JPP*).

The articles serve as the foundation for the company's first fusion power plant project, which Type One Energy is developing with the Tennessee Valley Authority utility in the United States.

Alex Schekochihin, Professor of Theoretical Physics at the University of Oxford and Editor of the *JPP*, spoke with enthusiasm about this development:

"*JPP* is very proud to provide a platform for rigorous peer review and publication of the papers presenting the physics basis of the Infinity Two stellarator—an innovative and ground-breaking addition to the expanding family of proposed fusion power plant designs.

"Fusion science and technology are experiencing a period of very rapid development, driven by both public and private enthusiasm for fusion power.

"In this environment of creative and entrepreneurial ferment, it is crucial that new ideas and designs are both publicly shared and thoroughly scrutinized by the scientific community—Type One Energy and *JPP* are setting the gold standard for how this is done (as we did with Commonwealth Fusion Systems five years ago for their SPARC physics basis)."

The new physics design basis for the pilot power plant is a robust effort to consider realistically the complex relationship between challenging, competing requirements that all need to function together for fusion energy to be possible.

This new physics solution also builds on the operating characteristics of high-performing stellarator fusion technology—a stellarator being a machine that uses complex, helical magnetic fields to confine the plasma, thereby enabling scientists to control it and create suitable conditions for fusion. This technology is already being used with success on the world's largest research stellarator, the Wendelstein 7-X, located in Germany, but the challenge embraced by Type One Energy's new design is how to scale it up to a pilot plant.

Building the future of energy

Functional fusion technology could offer limitless clean energy. As global energy demands increase and energy security is front of mind, too, this new physics design basis comes at an excellent time.

Christofer Mowry, CEO of Type One Energy, is cognizant of the landmark nature of his company's achievement and proud of its strong, real-world foundations.

"The physics basis for our new fusion power plant is grounded in Type One Energy's expert knowledge about reliable, economic, electrical generation for the power grid. We have an organization that understands this isn't only about designing a science project."

This research was developed collaboratively between Type One Energy and a broad coalition of scientists from national laboratories and universities around the world. Collaborating organizations included the US Department of Energy, for using their supercomputers, such as the exascale Frontier machine at Oak Ridge National Laboratory, to perform its physics simulations.

While commercial fusion energy has yet to move from theory into practice, this new research marks an important and promising milestone. Clean and abundant energy may yet become reality.

More information: Physics basis of the Infinity Two fusion power plant, *Journal of Plasma Physics* (2025). www.cambridge.org/core/journal … o-fusion-power-plant

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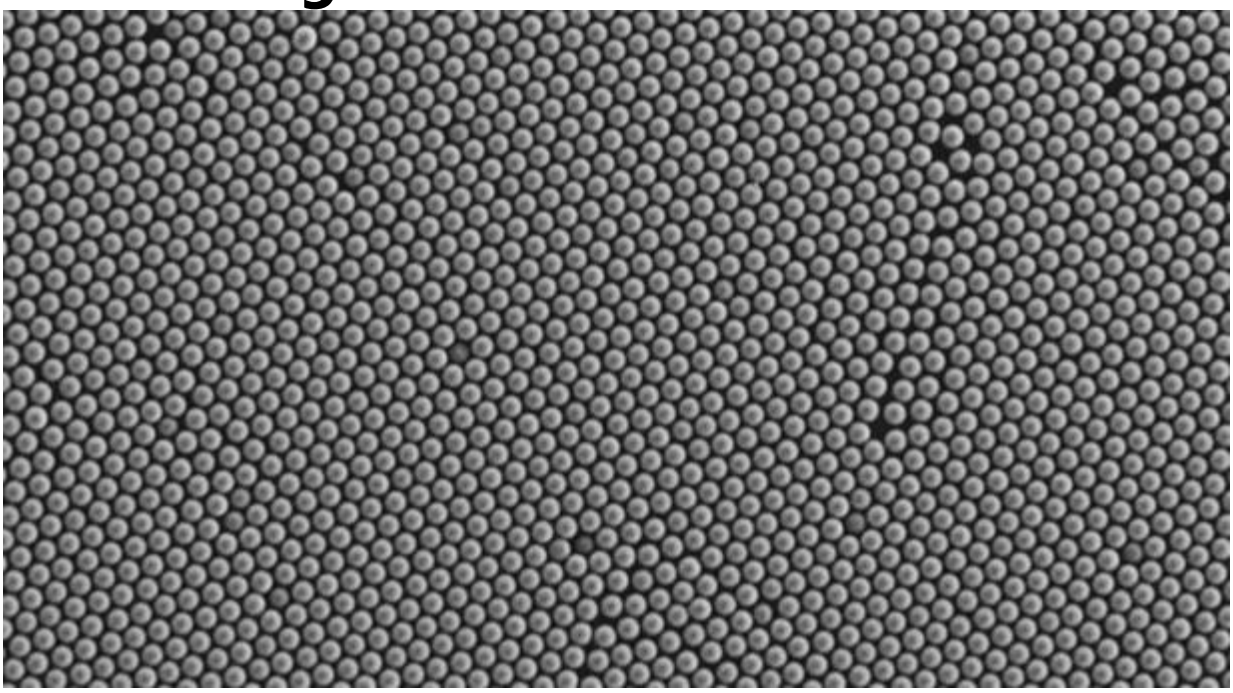
Tiny electricity-generating plastic beads could cut global fossil fuel reliance



Tiny electricity-generating plastic beads could cut global fossil fuel reliance

The world's energy demand is continuously increasing, with fossil fuels such as petroleum, natural gas, coal, oil shales, tar sands, bitumens, and heavy oils remaining the primary source.

These, however, release massive amounts of carbon dioxide (CO_2) when burned, making them the leading cause of climate change. This, in turn, fuels global warming, alters weather patterns, worsens natural disasters, and endangers both ecosystems and human health.

With global energy consumption projected to rise by 50% from 2005 to 2030, it's no surprise that researchers are increasingly seeking alternative energy sources to meet demand while reducing environmental impact.

Now, in a bid to address rising energy demand, researchers have come up with an unconventional way to produce electricity by using tiny plastic beads. When positioned next to each other and brought into contact, the beads appeared to generate more energy than usual, through triboelectrification.

The phenomenon, known as the triboelectric effect, occurs when physical contact between two dielectric materials generates triboelectric charges on their surfaces, similar to how rubbing a balloon against hair creates static electricity.

A closer look at the research

The team, consisting of scientists from the Department of Chemical Engineering at Vrije Universiteit Brussel (VUB), Riga Technical University, the Royal Melbourne Institute of Technology, and the MESA+ Institute at the University of Twente, focused on triboelectric nanogenerators (TENGs) in their study. Capable of converting mechanical movement into electrical energy, these devices rely on the interaction between materials to generate charge.

The current research reveals that when a tightly packed surface of small beads touches another surface with identical beads, some of them gain a positive charge while others become negatively charged. Ultimately, greater charge transfer boosts electricity production.

After conducting tests with various bead types, researchers discovered that size and material are crucial factors, with larger beads generally acquiring a negative charge, while smaller ones are more likely to become positively charged.

However, melamine-formaldehyde (MF) beads exhibited the most significant effect, demonstrating superior charge retention and transfer efficiency. This occurred because the material's low elasticity allowed it to retain and transfer electric charge more effectively.

According to the researchers, using beads not only provides a more affordable alternative to costly TENG technology but also improves sustainability by eliminating the need for solvents through dry fabrication.

Future energy technologies

The scientists believe that innovations in triboelectrification could open the door to novel energy-harvesting technologies capable of functioning independently of batteries or external power sources.

They point out that smart clothing, which converts motion into energy, and self-powered devices that require no charging are getting closer to becoming a reality. As a result, wearable technology and sustainable energy solutions are poised to benefit from this innovation.

“Our research shows that small changes in material selection can lead to significant improvements in energy generation efficiency,” Ignaas Jimidar, PhD, a postdoctoral researcher at VUB and lead author of the study, says in a press release. “This opens up new possibilities for triboelectric nanogenerators in everyday life, without reliance on traditional energy sources.”

Nevertheless, Jimidar points out that despite the promising potential, significant work remains to improve efficiency and reliability before the technology can be widely applied. The study has been published in the journal *Small*.

Nuclear Power Is Back. And This Time, AI Can Help Manage the Reactors.

A control room simulator at the Palisades Nuclear Generating Station in Covert, Mich. The average age of nuclear power plants in the U.S. is 42.© Don Campbell/The Herald-Palladium/Associated Press

A revival in nuclear power—partly fed by ravenous demand from data centers for artificial intelligence—is leading to greater interest in harnessing AI to make those nuclear plants more efficient.

The Energy Department's Argonne National Laboratory, based in Lemont, Ill. and known for its work on nuclear reactors, has developed an AI-based tool that can assist with reactor design and help operators run nuclear plants, according to Richard Vilim, a senior nuclear engineer within the lab's nuclear science and engineering division.

Argonne's tool, called the Parameter-Free Reasoning Operator for Automated Identification and Diagnosis, or PRO-AID, marks a technological leap in a field that saw its heyday in the last quarter of the 20th century.

"The nuclear plants were built over 30 years ago," Vilim said, "so they're kind of dinosaurs when it comes to technology."

Today, nearly all of the nation's 94 operating nuclear reactors have had their licenses extended, and together still provide almost 20% of U.S. electricity. Their average age is roughly 42, according to the U.S. Energy Information Administration.

Argonne's plan is to offer PRO-AID to new, tech-forward nuclear builds, but it's also eyeing the so-called dinosaurs, some of which are being resurrected by companies like Amazon and Microsoft to help power their AI data centers. The global push for AI is poised to fuel a sharp rise in electricity demand, with consumption from data centers expected to more than double by the end of the decade, the International Energy Agency said Thursday.

The owners of roughly a third of U.S. nuclear plants are in talks with tech companies to provide electricity for those data centers, the Wall Street Journal has reported.

PRO-AID performs real-time monitoring and diagnostics using generative AI combined with large language models that notify and explain to staff when something seems amiss at a plant. It also uses a form of automated reasoning—which uses mathematical logic to encode knowledge in AI systems—to mimic the

way a human operator asks questions and comes to understand how the plant is operating, Vilim said.

The tool can also help improve the efficiency of the personnel needed to operate a nuclear plant, Vilim said. That's especially important as older employees leave the workforce. "If we can hand off some of these lower-level capabilities to a machine, when someone retires, you don't need to replace him or her," he said.

Compared with gas-powered plants—which are newer, and more automated with digital monitoring tools—the technology at nuclear plants is far behind, Vilim added. Part of the efficiency in updating technology will come from consolidating the monitoring staff at a utility's nuclear plants at a single, centralized location—much as gas-powered plants already do.

For legacy nuclear plants, however, it's not always obvious that the technology is worth the cost, said Vilim. PRO-AID, a tool that can be licensed to a software developer or nuclear supplier, hasn't yet found its way into a commercial nuclear plant.

While some power plants might want to update with technology, it's also a challenge to take power off the grid for an extended period of time in order to upgrade it, said Bob Johnson, an analyst at market research and IT consulting firm Gartner.

"The utilities are faced with, 'Is there sufficient value in putting this in? Or do we have what we need and we just go to the finish line, which might be just 20 years away?'" Vilim said.

Bill Gates-founded TerraPower, one of a newer generation of nuclear companies, has been using advanced computer modeling to design its reactor technologies since its start in the early aughts, the company said. TerraPower's Natrium reactor will be the first to be designed and modeled "from inception to commercialization in a completely digital environment," said Chris Levesque, the company's president and chief executive.

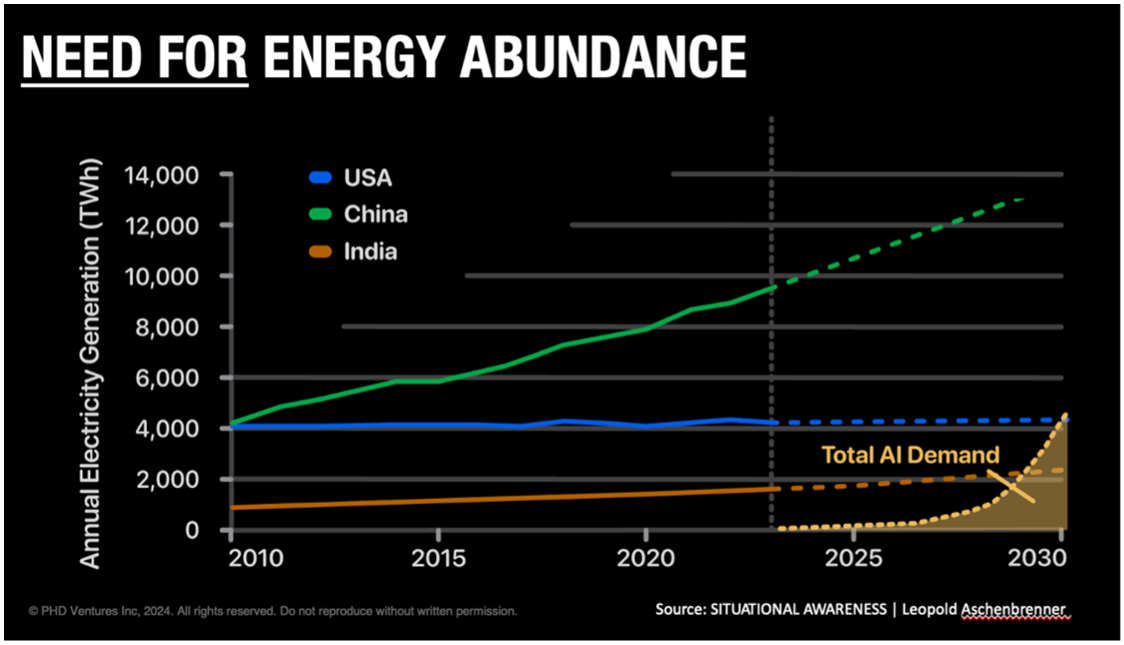
The Sam Altman-backed nuclear startup Oklo has been using AI to do design analysis on its reactors. With the help of those tools, it's possible to reduce the amount of time needed to run high-fidelity simulation cases, said Jacob DeWitte, Oklo's co-founder and chief executive.

Still, it will take time for AI to fully arrive in commercial nuclear power, he said.

"It is a big accelerator, it's a massive productivity accelerant," DeWitte said. "But to be candid, I think nuclear is really, really early in the days of this."

Time to FULLY embrace nuclear. Not the old problematic nuclear plants (e.g., Three Mile Island and Fukushima), but advanced, fail-safe, Gen-IV nuclear systems that deserve your love and support. Next will come small modular reactors (SMRs), and then fusion plants.

Below is a chart that should concern you. Bottom line, total electricity demand for AI by the end of this decade could consume 100% of our energy output. We need to scale electricity production FAST.



The Benefits of Nuclear Power

Nuclear energy is one of the cleanest and most reliable power sources available, preventing 2 billion tons of CO2 emissions yearly—equivalent to slashing one-third of cars globally. Nuclear energy's low carbon footprint is staggering: a single uranium pellet rivals 1 ton of coal, delivering over 50% of U.S. carbon-free electricity.

There are 3 technologies leading this resurgence in nuclear energy:

Gen-IV Nuclear Technology

Generation-IV nuclear reactors represent a quantum leap beyond conventional nuclear plants. Using alternative coolants like molten salt and operating in closed fuel cycles, these systems dramatically improve efficiency, safety, and waste management. Since 2020, over $3 billion in private investment has flowed to Gen-IV startups, accelerated by government support programs.

Leaders in Gen-IV Technology

Kairos Power signed a groundbreaking contract with Google to deploy multiple advanced reactors, supplying 500MW of power. Founded in 2016, Kairos uses molten fluoride salt coolant and meltdown-proof fuel pebbles. Their first reactor is expected online in 2030, with additional deployments through 2035. CEO Mike Laufer notes this Google contract allows Kairos to "scale infrastructure and manufacturing capabilities."

Terrestrial Energy, founded in 2013, is pioneering its Integral Molten Salt Reactor (IMSR). Having recently gone public in a $280 million SPAC deal, their design features a reactor core replaced every seven years to mitigate corrosion issues. Texas A&M University has selected Terrestrial to partner on a commercial IMSR plant at its RELLIS campus.

TerraPower, founded by Bill Gates in 2006, uses sodium coolant in its Natrium technology with a molten salt-based energy storage system. The 345MW base capacity can boost to 500MW for over five hours. With $1 billion in private funding and $2 billion from the DOE, TerraPower began construction in Kemmerer, Wyoming in 2024 and aims to start operations by 2030.

Small Modular Reactors (SMRs)

SMRs are revolutionizing nuclear deployment through factory-built, shippable designs that slash costs and construction time. Their smaller footprint and enhanced safety features make them ideal for replacing fossil fuel plants and powering remote locations.

Leaders in SMR Technology

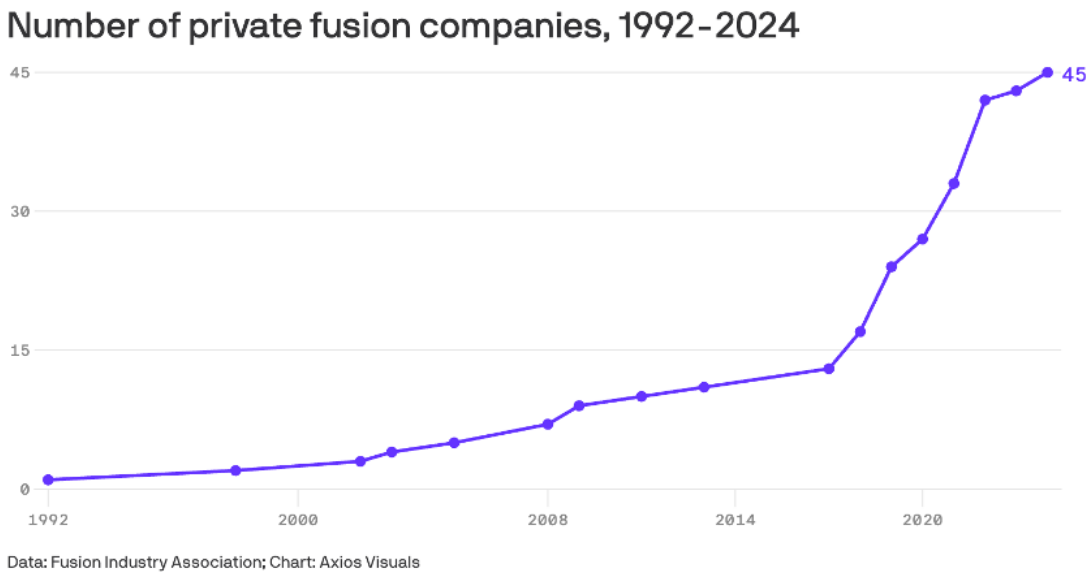
NuScale Power (2007) made history as the first company to receive SMR design certification from the U.S. Nuclear Regulatory Commission. Their 77MWe modules can be deployed in various configurations, with international collaborations in Romania and Poland. Their North American project with Standard Power to produce 2GW for data centers is set to go live in 2029, potentially becoming the first operational SMRs in the US.

X-Energy secured direct investment from Amazon—the first tech company to back an advanced reactor. Founded in 2009, they recently raised $700 million led by Amazon and investors including Citadel's Ken Griffin. Their 80MW Xe-100 reactors use helium coolant and proprietary graphite-encased fuel. X-Energy is partnering with Amazon to deliver 5GW of clean energy by 2039, with first plants expected online in the early 2030s.

Oklo, founded in 2013 and backed by Sam Altman, signed an agreement with Switch to deploy 12GW of nuclear power by 2044. Their Aurora reactor uses metallic fuel and high-assay low-enriched uranium. With environmental permits secured for its Idaho National Laboratory site, Oklo aims for operational status by 2027, making it potentially the earliest SMR to come online.

Fusion: The Ultimate Energy Source

Fusion represents the holy grail of energy: the same process powering our Sun. The 2022 breakthrough at Lawrence Livermore National Laboratory demonstrated more energy out than in for the first time, signaling that we're approaching commercial viability.



Source: Axios, Fusion Industry Associate

Leaders in Fusion Technology

Helion, founded in 2013 and backed by Sam Altman, recently raised $425 million, pushing its valuation to $5.2 billion. Their field-reversed configuration directly converts plasma collisions to electricity without steam turbines. Helion has a groundbreaking deal to supply Microsoft with electricity by 2028 – years ahead of competitors. Their seventh prototype, Polaris, went online in early 2025 and could become the first fusion reactor to generate commercial electricity.

Commonwealth Fusion Systems has secured $1.8 billion in Series B funding in 2021. Their tokamak design uses high-temperature superconducting tape to generate powerful magnetic fields. In March 2025, CFS installed the cryostat base for their SPARC demonstration reactor. Backed by Breakthrough Energy Ventures and Bill Gates, CFS expects their commercial-scale Arc reactor to be operational in the early 2030s.

TAE Technologies, founded back in 1998, has raised $1.3 billion from Alphabet, Chevron Ventures, and Venrock. Their approach uses particle beams to stabilize plasma in a cigar shape. With 1,500+ patents, TAE is building their Copernicus device

to demonstrate fusion-relevant conditions, targeting a commercial Da Vinci power plant generating 350-500MWe by the 2030s.

Pledges to address the climate crisis have shown to be frail and projected electricity and energy demand is set to outpace our current infrastructure. Yet this is our chance: with AI's momentum and nuclear's strength, humanity has an opening to turn the tide on the climate crisis.

MADE-IN-CANADA FUSION BREAKTHROUGH COULD CHANGE THE FUTURE OF GLOBAL ENERGY

APRIL 9, 2025

As energy companies and governments worldwide pursue the next advancements in clean energy, Canadian energy company General Fusion has achieved a world-first fusion breakthrough with its creation of a magnetized plasma in a target chamber using its new machine, Lawson Machine 26 (LM26).

With plasma being created daily in the machine, by compressing plasmas with a lithium liner to create fusion and heating from compression, the team at General Fusion has been tweaking the system to move to the next phase, which is compressing the plasma to create fusion and release energy. The end goal for the company is to produce zero-carbon fusion power that could provide clean electricity to homes and businesses globally.

Earlier this year, the company's achievement was detailed in a new peer-reviewed paper that appeared in *Nuclear Fusion.*

"The largest energy confinement times have been obtained for discharges with a broad plasma current profile, fresh lithium coating on the device walls, and a near constant toroidal field," read a portion of the paper's abstract. With plasmas generating thermal confinement times exceeding 10 milliseconds, the meter-scale

plasmas the LM26 produces "can thus achieve significant heating if compressed on a timescale of milliseconds."

General Fusion uses a mechanical compression system with a liquid metal liner, but how novel or risky is this approach in the fusion world?

"This research is safe and won't cause any health or environmental problems," Jason Donev, a Professor in the Faculty of Science, Department of Physics and Astronomy at the University of Calgary who was not involved in the new research, told *The Debrief* in an email. "I'm always in favour of research. General Fusion's methods are a novel approach to the problem of fusion, they've been pursuing this for a while and many people are excited to see what they can come up with."

ROAD MAP TO A FUSION BREAKTHROUGH

On December 23, 2022, a historical breakthrough occurred when scientists at the U.S. National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL) achieved fusion ignition for the first time. Although it still may be a long road toward making practical use of fusion across all sectors, scientists consider it a valuable, affordable, clean, and renewable energy source and are working steadily toward making it a day-to-day reality.

With 20 years of research dedicated to designing the science around LM2, crafting the machine only took 16 months to build. Dr. Michel Laberge, founder and chief science officer of General Fusion, explained the mechanics behind the project.

"We've built 24 plasma injectors, created over 200,000 plasmas, and generated fusion neutrons from plasma compressions – de-risking LM26 and preparing us for this new chapter at General Fusion," Laberge said in a statement.

"We're ready to make some fusion happen in LM26!"

GENERAL FUSION'S TECHNOLOGY PROGRESSES

The machine is already making progress, working towards a core heat of 100 million degrees Celsius (the same temperature as the Sun) in its environment to create fusion.

General Fusion technology differs from its competitors as it uses mechanical compression to spark fusion without the need for magnets or lasers, a method that has proven to be more practical and cost-efficient when building power plants.

"We are doing what we do best – nimbly advancing our transformative technology and getting real results that matter," said Greg Twinney, CEO, General Fusion. "Unlike other approaches, MTF is designed from the ground up to produce practical power. As a result, our path to delivering clean fusion energy to homes and businesses following LM26 is more straightforward and streamlined than other technologies."

A MADE-IN-CANADA FUSION BREAKTHROUGH

Government leaders across Canada are considering this a huge milestone and a win in the global race for clean energy. Calling it a "made-in-Canada" innovation is once again putting Canada at the forefront and as leaders in clean energy technology.

"General Fusion's work is reinforcing Canada's status as a powerful innovator in nuclear science and technology," said the Honourable Jonathan Wilkinson, Minister of Natural Resources Canada.

"General Fusion is a homegrown success story showing the value of Canadian innovation," said the Honourable François-Philippe Champagne, Minister of Innovation, Science and Industry, in a press release. "We are proud to champion their progress as they advance their incredible clean fusion energy technology."

“I’m glad smart people, including those at General Fusion, are working hard to solve the difficult problem of commercial fusion,” Donev told *The Debrief*. “Commercial fusion would transform the world as much of cell phones, personal computers or automobiles have.”

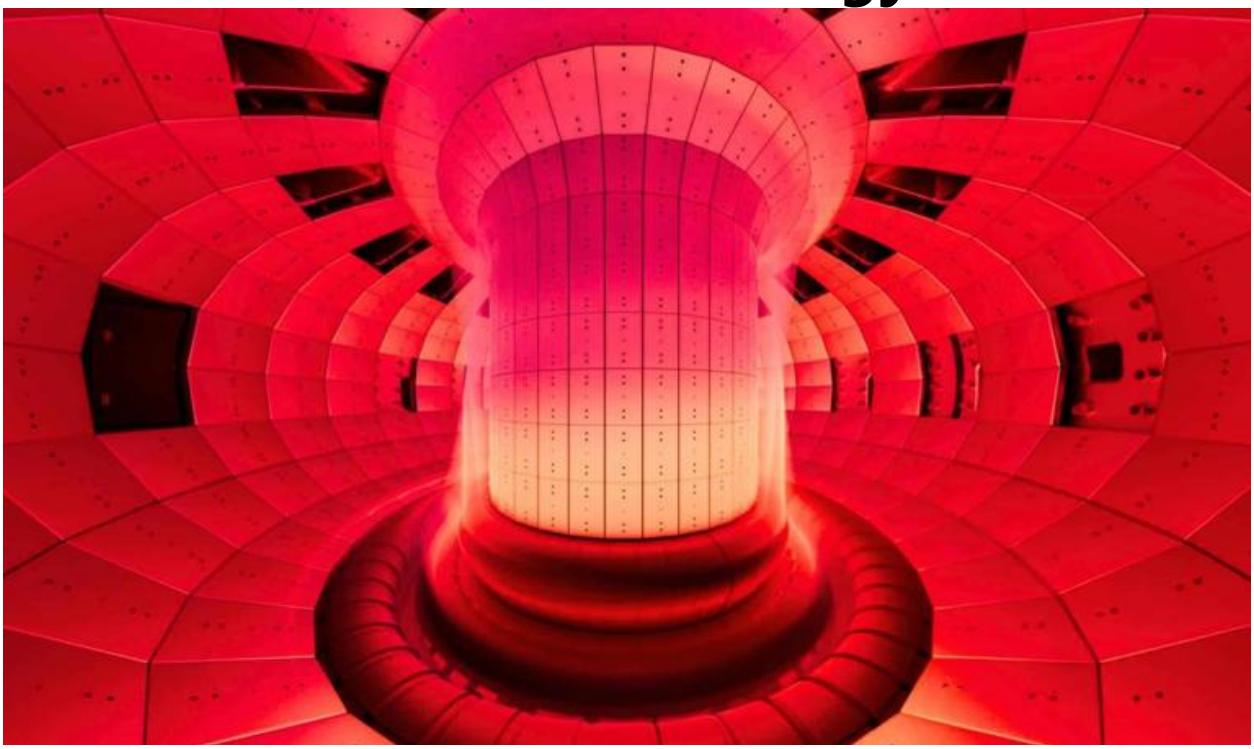
“The world needs to aggressively pursue fusion, along with other low carbon sources of energy like fission, solar, wind, hydro and so forth,” he added. “Climate change is here, [it’s] bad, our fault, and we need to do *everything* we can to change how the world gets energy.”

“Fusion will take a while though and we can’t just wait for fusion to save us,” Donev still cautioned, despite his overall optimism for a fusion energy future. “We need to pursue other avenues while continuing to research fusion.”

The new paper, “Thermal energy confinement time of spherical tokamak plasmas in PI3,” by A. Tancetti, C. Ribeiro, et al, appeared in *Nuclear Fusion.*

This article was updated on 4/10/25 with additional quotes from Professor Jason Donev.

Scientists Achieve Record-Breaking Fusion Stability, Bringing Us One Step Closer to Clean Infinite Energy



For decades, **nuclear fusion** has been hailed as the holy grail of **clean energy**—a virtually limitless power source that could revolutionize how we fuel our world. Yet, the path to achieving **stable fusion** has been fraught with challenges, requiring temperatures hotter than the sun and precision control of unruly **plasma**.

Now, a team led by Dr. Anne-Isabelle Etienvre of the French Atomic Energy Commission (CEA) in southern France has shattered records by maintaining plasma for an unprecedented **22 minutes**, marking a significant leap toward making fusion energy a reality.

The Science of Fusion: Why Plasma Stability Matters

Nuclear fusion, the process that powers the sun, involves fusing light atomic nuclei to release immense amounts of energy. For this reaction to occur on Earth, particles must be heated to temperatures exceeding **100 million degrees Celsius** (over 1.8 million degrees Fahrenheit). At these extreme temperatures, atoms collide at incredible speeds, forming a plasma—a superheated, electrically charged gas.

However, maintaining **plasma stability** is no small feat. Any imbalance in magnetic fields or external factors can cause the plasma to cool or escape its **magnetic confinement**, disrupting the reaction. **Tokamaks**, like the one used in this experiment, rely on precise electromagnetic control to keep plasma hot and stable. The recent **22-minute record** demonstrates significant progress in overcoming these challenges.

Dr. Etienvre succinctly captured the significance of this achievement: "Experiments will continue with increased power," she said, hinting at the next steps in pushing the boundaries of fusion research.

The team's work took place at the CEA's tokamak facility in **Cadarache**, southern France, a hub for cutting-edge fusion research. This record surpasses a previous milestone set by a Chinese team, highlighting the competitive yet collaborative nature of global fusion efforts.

A Global Effort: The Role of International Collaboration

The record-breaking experiment in France is part of a broader, international effort to harness fusion energy. The **International Thermonuclear Experimental Reactor (ITER)**, currently under construction in Saint-Paul-lès-Durance, southern France, represents the pinnacle of this collaboration.

ITER brings together 35 countries, including China, the European Union, India, Japan, South Korea, Russia, and the United States, in a shared mission to build the world's largest tokamak.

While ITER's completion has faced delays, smaller-scale experiments like the one in France are crucial for refining the technology. Each milestone, such as the 22-minute plasma record, provides valuable insights that can be integrated into ITER's design.

ITER's tokamak will stand 30 meters tall and weigh 23,000 tons, making it the largest of its kind. Its primary goal is to achieve a **tenfold energy gain**, producing 500 megawatts of power from 50 megawatts of input. First plasma is expected in the late 2020s, with full-scale operations anticipated by the 2030s.

Fusion vs. Fission: A Cleaner Path to Energy

Unlike **nuclear fission**, which splits atoms and produces long-lived radioactive waste, fusion combines hydrogen nuclei to form helium, generating minimal radioactive byproducts. This makes fusion a far cleaner and safer alternative. Additionally, fusion relies on **hydrogen**, the most abundant element in the universe, offering a nearly inexhaustible energy source.

Despite its promise, fusion has faced significant obstacles, including high costs and technical complexities. However, recent advancements, such as the 22-minute plasma record and Europe's **Joint European Torus (JET)** achieving 59 megajoules of sustained fusion energy in 2022, suggest that the field is gaining momentum.

The environmental benefits of fusion are particularly compelling. According to the **Intergovernmental Panel on Climate Change (IPCC)**, transitioning to low-carbon energy sources is critical to achieving **net-zero emissions**. Fusion's ability to generate power without producing greenhouse gases or long-lived radioactive waste positions it as a key player in the global energy transition.

The Road Ahead: Scaling Up for Commercial Viability

While the 22-minute plasma record is a remarkable achievement, the journey to **commercial fusion power** is far from over. Researchers must now focus on scaling up the technology to achieve **net energy gain**—where a reactor produces more energy than it consumes. This requires extending plasma stability from minutes to hours and increasing energy output to commercially viable levels.

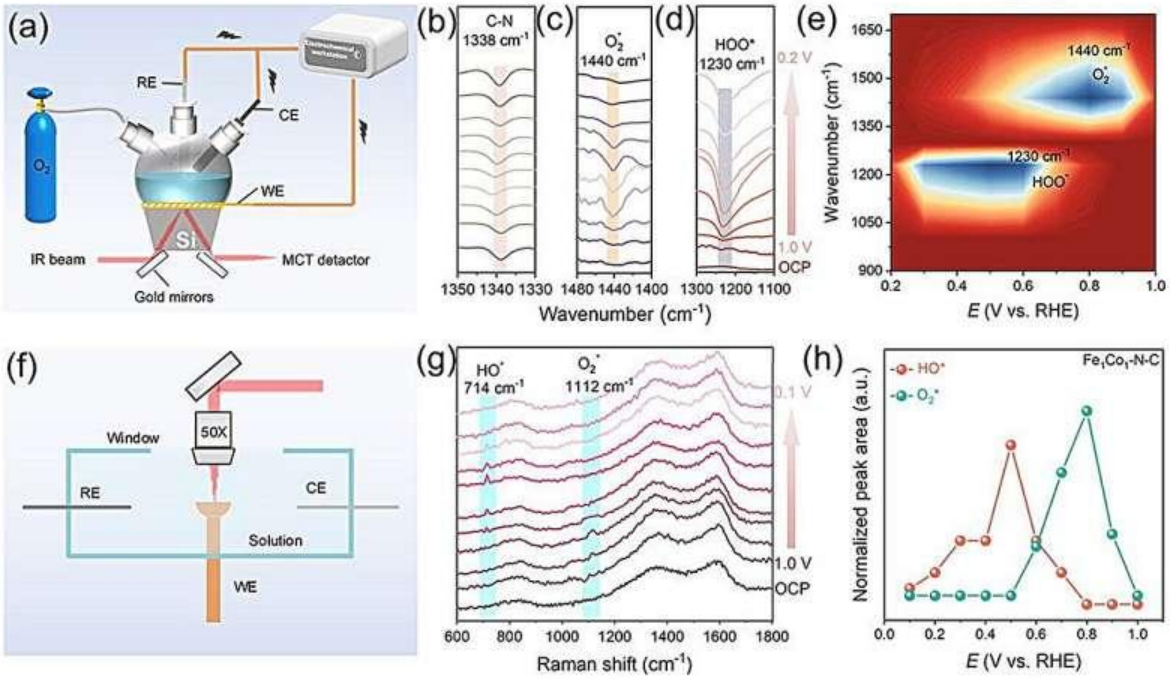
Next steps in fusion research include extending plasma duration to several hours, improving energy output to achieve net energy gain, and reducing contamination within the reaction chamber. Even minor impurities can disrupt the delicate environment needed for fusion to thrive.

The CEA team in **Cadarache** is already planning further experiments to push the boundaries of plasma stability. By increasing power and refining control mechanisms, they aim to demonstrate that fusion can be sustained for longer periods and at higher temperatures. These efforts are critical for proving that fusion can meet the energy demands of the real world.

MAY 15, 2025

Dual-atom catalyst boosts performance of zinc-air batteries for real-world applications

by Tohoku University



In-situ ATR-SEIRAS and in-situ Raman studies for ORR mechanism. Credit: *Energy & Environmental Science* (2025). DOI: 10.1039/D5EE00215J

A research team has unveiled a breakthrough in improving the performance of zinc-air batteries (ZABs), which are an important energy storage technology. This breakthrough involves a new catalyst that significantly boosts the efficiency of the oxygen reduction reaction (ORR), a crucial process in ZABs. The development could lead to more efficient, long-lasting batteries for practical applications.

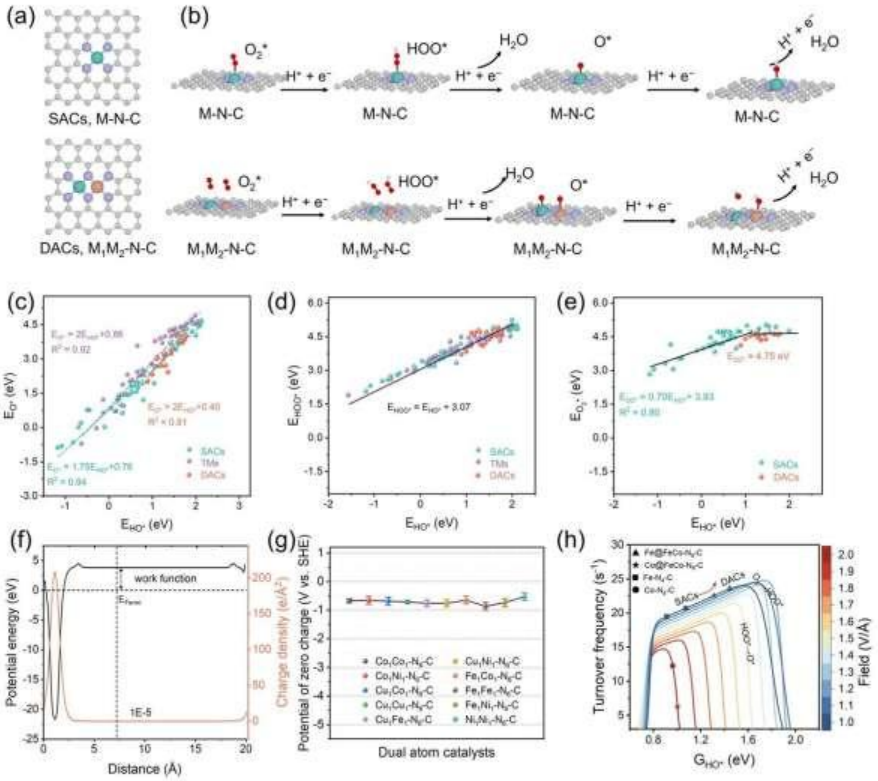
The study is published in the journal *Energy & Environmental Science*.

The oxygen reduction reaction is a critical step in many energy conversion devices, including ZABs. However, the reaction often suffers from slow kinetics, which limits the performance of the batteries. To solve this, platinum-based catalysts are typically used, but they are expensive, scarce, and can be poisoned by impurities.

Researchers have been searching for alternatives that are both cost-effective and highly efficient. This study focuses on a new class of catalysts called dual-atom catalysts (DACs), which consist of two metal atoms closely paired together to enhance catalytic activity.

The team, led by Di Zhang, assistant professor at Tohoku University's Advanced Institute of Materials Research (WPI-AIMR), used a combination of computational modeling and experimental techniques to design and create a dual-atom catalyst made of iron (Fe) and cobalt (Co), which are combined with nitrogen (N) and carbon (C) in a porous structure.

This catalyst, named Fe_1Co_1-N-C, was identified as the optimal catalyst for the oxygen reduction reaction in alkaline conditions. The unique combination of materials allows the catalyst to function efficiently, making it a promising candidate for use in ZABs.



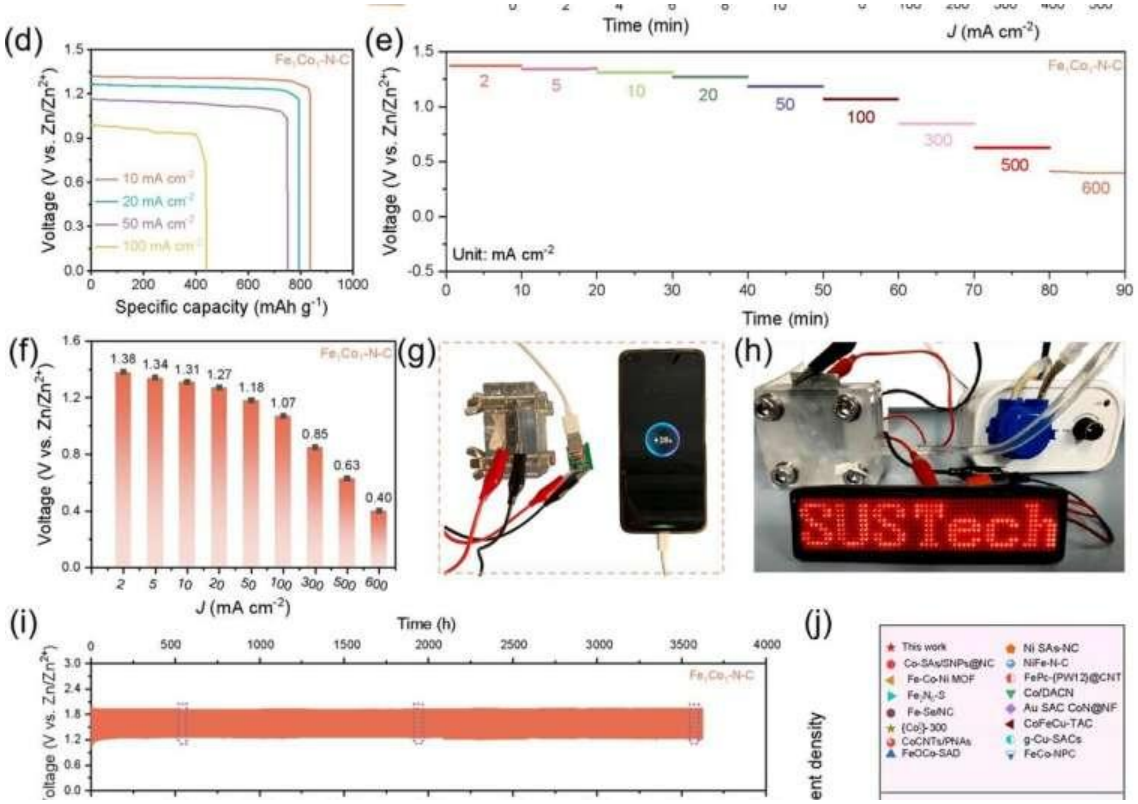
pH-field coupled microkinetic modeling of DACs in ORR. Credit: *Energy & Environmental Science* (2025). DOI: 10.1039/D5EE00215J

The researchers designed the Fe_1Co_1-N-C catalyst by first using a model to predict how pH (acidity) affects the reaction. This guided them in the creation of a catalyst with the right properties for maximum efficiency. They then synthesized the catalyst using a method that involved hard templates and a CO_2 activation process to create a structure that has small pores. These pores are essential for allowing reactants to move through the material, which improves the overall catalytic performance.

The Fe_1Co_1-N-C catalyst showed a significantly higher oxygen reduction activity than the commonly used platinum catalyst (Pt/C). In practical terms, the Fe_1Co_1-N-C-based zinc-air batteries demonstrated a high open-circuit voltage of 1.51 volts, meaning they can generate a substantial amount of energy.

Additionally, the batteries displayed an energy density of 1,079 watt-hours per kilogram of zinc (Wh $kgZn^{-1}$), which is an excellent measure of energy storage capability.

In addition to the high voltage and energy density, the Fe_1Co_1-N-C-based batteries also demonstrated an excellent rate capability, meaning they can perform well even when subjected to high current densities—ranging from 2 to 600 milliamps per square centimeter (mA cm^{-2}). More remarkably, the batteries showed an ultra-long lifespan, lasting over 3,600 hours and completing 7,200 cycles under a moderate current, which is far superior to most other batteries.



ZAB performance. Credit: *Energy & Environmental Science* (2025). DOI: 10.1039/D5EE00215J

Zhang explains, "This work provides an efficient and rational strategy for designing and synthesizing catalysts that can be used in real-world applications. By combining theoretical models with practical synthesis methods, we were able to develop a catalyst that can significantly improve the performance of zinc-air batteries."

Looking ahead, Zhang and his team plan to continue their research by developing even more advanced methods to create dual-atom catalysts with precise atomic pairings. They also intend to enhance techniques for identifying the specific active sites in the catalysts. These efforts aim to further optimize the performance of energy conversion technologies and make them even more efficient and cost-effective for widespread use.

More information: Tingting Li et al, A pH-dependent microkinetic modeling guided synthesis of porous dual-atom catalysts for efficient oxygen reduction in Zn–air batteries, *Energy & Environmental Science* (2025). DOI: 10.1039/D5EE00215J

Journal information: Energy & Environmental Science
Provided by Tohoku University

APRIL 23, 2025

Is nuclear power the key to a low-carbon future?

by Najmedin Meshkati, University of Southern California

Credit: Pixabay/CC0 Public Domain

Najmedin Meshkati is professor of civil and environmental engineering, industrial systems engineering and international relations at the USC Viterbi School of Engineering. The following is an expanded answer to USC News' question "What role will nuclear energy play in the future?"

The world faces an energy demand explosion of historic proportions. With the global population racing toward 9 billion people, electricity requirements are projected to skyrocket from today's 9,000 gigawatts to a staggering 15,000 gigawatts by 2050—a 70% surge that dwarfs all previous energy transitions in human history.

This isn't merely abstract growth. Consider AI infrastructure alone: By 2030, data centers will demand 160% more power than today, consuming electricity equivalent to Canada's

entire national output (approximately 650 terawatt hours annually). This single technological sector will require more power than 38 million American homes combined.

The International Energy Agency confirms this trajectory, projecting that emerging economies will account for 90% of electricity demand growth through 2050, with India's per-capita electricity consumption set to double within just 15 years. Meanwhile, China already consumes more electricity than the United States, European Union and Japan combined—yet still has substantial growth ahead.

These aren't speculative forecasts but mathematical certainties driven by industrial development, rapid urbanization and technological revolution. Without unprecedented energy innovation, we face a future where demand dramatically outstrips supply, creating economic instability and geopolitical conflict over increasingly scarce resources.

Nuclear energy stands poised to serve as a cornerstone of the global transition to a low-carbon future. Unlike intermittent renewable sources such as wind and solar, nuclear power provides reliable, large-scale baseload electricity that can stabilize energy grids and complement clean energy portfolios. Recent policy and industry developments underscore this renewed momentum.

By 2050, nuclear energy capacity is expected to triple globally to meet net-zero emissions targets, as pledged by 22 countries at COP28 in Dubai in December 2023. Since the initial pledge at COP28, six additional nations have joined the declaration at COP29 in November 2024.

The planned restart of the Palisades nuclear power plant in Michigan, which was shut down in 2022, and Unit 1 of the Three Mile Island nuclear power plant, which was not involved in the 1979 accident but was shut down in 2019 due to economic challenges, is expected by mid-2028. Reports indicate that the Duane Arnold nuclear plant in Iowa, which ceased operations in 2020, may also pursue a restart.

This unprecedented trend would mark the first time in U.S. history that decommissioned nuclear plants are brought back online, enabled by federal and bipartisan political support. According to recent reports, due to the unexpectedly slow expansion of renewable energy in Germany, there is a vocal and growing movement to restart some of the country's 11 shutdown nuclear power reactors.

Emerging nuclear technologies offer promising pathways for overcoming many legacy challenges associated with traditional nuclear energy. Small modular reactors (SMRs) promise to reduce costs, construction timelines and land use while enhancing safety features through passive cooling and underground containment.

Additionally, advanced reactor designs—such as molten salt, gas-cooled and thorium-fueled systems—are being developed for greater efficiency and reduced waste generation. These innovations could revolutionize the energy landscape in the coming decades by providing nearly limitless, carbon-free power with minimal safety and waste concerns.

Nuclear fusion, once considered the "holy grail" of energy, has reemerged as a promising energy frontier, with recent breakthroughs bringing practical applications within reach. Unlike fission, fusion offers distinct advantages: minimal radioactive waste, no meltdown risk and fuel derived from abundant resources.

The National Ignition Facility's December 2022 achievement of ignition, producing more energy than consumed, marked a historic turning point. This success has catalyzed investment and innovation. Meanwhile, international projects such as ITER continue advancing plasma control capabilities.

Though material engineering challenges persist in handling fusion's extreme conditions, the field has decidedly shifted from theoretical to technological—potentially delivering a safe, clean and limitless energy source.

To fully realize nuclear energy's potential, a multipronged policy approach is essential. Governments must invest in financing mechanisms—such as loan guarantees, production tax credits and public-private partnerships—to de-risk nuclear investment. Regulatory frameworks should be modernized to streamline licensing while maintaining rigorous safety standards. Public engagement campaigns must be launched to rebuild trust in nuclear energy through transparent communication and community involvement.

Above all, nuclear power must be integrated strategically with renewables in national and international energy plans. If these challenges are met with the urgency and innovation they require, nuclear energy can become not only a viable option but a vital pillar of the clean energy transition.

After four decades of conducting rigorous nuclear safety research and inspections at power plants worldwide—including Three Mile Island, Chernobyl, Fukushima Daiichi and Fukushima Daini, I've reached an inescapable conclusion: The global nuclear power industry stands or falls as a single entity.

This tightly interconnected chain or interdependent network is fundamentally vulnerable as its weakest link. Today's resurgence of confidence in nuclear energy—this latest "nuclear renaissance" with its wave of logical expectations and (to paraphrase former Federal Reserve Chairman Alan Greenspan) "rational exuberance"—could collapse instantly under the weight of a single severe accident anywhere in the world.

History proves this cyclical pattern: The first renaissance after Three Mile Island was extinguished by Chernobyl, and the second was destroyed by Fukushima. Now, we are witnessing the third "nuclear renaissance" in just 46 years. The stark reality of this industry remains unchanged: "A nuclear accident anywhere is a nuclear accident everywhere."

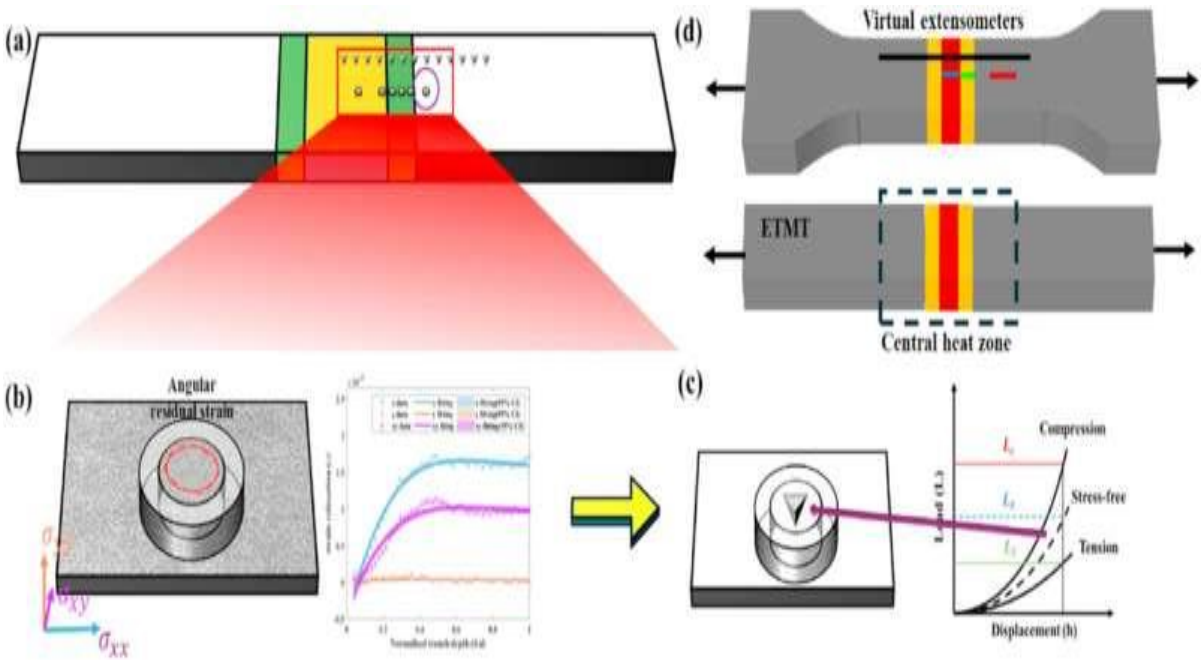
The imperative is clear: The global nuclear power industry must urgently intensify international, interdisciplinary collaborative efforts to bolster its safety culture, which is analogous to the human body's immune system that protects it against pathogens and fends off diseases, with particular focus on its most vulnerable operations. That's why this industry needs to double down on collaborative efforts, by utilizing engineering diplomacy, to improve its safety culture, especially for its weakest members.

Provided by University of Southern California

APRIL 29, 2025

Engineers develop technique to enhance lifespan of next-generation fusion power plants

by University of Surrey



(a) Laser-welded P91 specimen for residual stress, microstructures (EBSD and SEM) and micro-hardness characterization, (b) the PFIB-DIC ring-core residual stress quantification, (c) the nanoindentation residual stress measurement, where the ring-core fabricated during PFIB-DIC measurement provides a stress-free reference, (d) the dog-bone specimen used in the room temperature uniaxial tensile test and virtual extensometers applied in DIC analysis, and the rectangular sample for high-temperature tensile testing using the electro-thermal mechanical testing. Credit: *Journal of Materials Research and Technology* (2025). DOI: 10.1016/j.jmrt.2025.02.260

As the world races to build the first commercial nuclear fusion plant, engineers from the University of Surrey have made a breakthrough in understanding how welded components behave inside the extreme conditions of a reactor—offering critical insights for designing safer and longer-lasting fusion energy systems.

Working in collaboration with the UK Atomic Energy Authority (UKAEA), the National Physical Laboratory, and global supplier of scientific instruments for nanoengineering

TESCAN, researchers have developed and used an advanced microscopic method to map hidden weaknesses locked inside welded metals during manufacturing that can compromise reactor components and reduce their lifespan.

The research, published in the *Journal of Materials Research and Technology*, details how they examined P91 steel—a very strong and heat-resistant metal candidate for future fusion plants. Researchers applied an advanced imaging technique using a plasma-focused ion beam and digital image correlation (PFIB-DIC) to map residual stress in ultra-narrow weld zones that were previously too small to study with conventional methods.

Results showed that internal stress has a big impact on how P91 steel performs—beneficial stress making some areas harder and detrimental stress making others softer, which affects how the metal bends and breaks. At 550°C, the temperature expected in fusion reactors, the metal became more brittle and lost more than 30% of its strength.

Dr. Tan Sui, Associate Professor (Reader) in Materials Engineering at the University of Surrey who is leading the research, said, "Fusion energy has huge potential as a source of clean, reliable energy that could help us to reduce carbon emissions, improve energy security and lower energy costs in the face of rising bills. However, we first need to make sure fusion reactors are safe and built to last.

"Previous studies have looked at material performance at lower temperatures, but we've found a way to test how welded joints behave under real fusion reactor conditions, particularly high heat. The findings are more representative of harsh fusion environments, making them more useful for future reactor design and safety assessments."

Fusion energy—the process that powers the sun and stars—fuses light atoms to release massive amounts of energy. Unlike traditional nuclear power, the materials used, and the radioactive waste produced, are generally short-lived and far less hazardous.

Beyond the lab, the data from the team provides a foundation for validating finite element simulation models and machine learning-powered predictive tools, which have great potential to accelerate the design of fusion reactors like the UK's STEP program and the EU's DEMO power plant project. This will help researchers to refine predictions and focus on the most positive material outcomes, significantly reducing experimental costs.

Dr. Bin Zhu, research fellow at the University of Surrey's Center for Engineering Materials and a key author of the study, said, "Our work offers a blueprint for assessing the structural integrity of welded joints in fusion reactors and across a wide range of extreme environments. The methodology we developed transforms how we evaluate residual stress and can be applied to many types of metallic joints. It's a major step forward in designing safer, more resilient components for the nuclear sector."

With the future commercialization of fusion power on the horizon, the research will play a crucial role in advancing the technologies needed to make it a reality—bringing us closer to delivering secure, low-carbon electricity at scale.

Jiří Dluhoš, FIB-SEM product manager at TESCAN, said, "We are proud that our FIB-SEM instruments can be part of such a crucial topic in materials research for the energy industry. Our long-standing collaboration with the University of Surrey to automate microscopic residual stress measurements proves that the plasma FIB-SEM can be successfully used for high-precision machining at the microscale."

More information: Bin Zhu et al, Assessing residual stress and high-temperature mechanical performance of laser-welded P91 steel for fusion power plant components, *Journal of Materials Research and Technology* (2025). DOI: 10.1016/j.jmrt.2025.02.260
Provided by University of Surrey

MAY 8, 2025

Q&A: What will it take to bring fusion energy to the US power grid?

by Erin Woodward, SLAC National Accelerator Laboratory

Inside the LCLS-II tunnel, taken April 6, 2022. Credit: Jim Gensheimer/SLAC National Accelerator Laboratory

Arianna Gleason is an award-winning scientist at the Department of Energy's SLAC National Accelerator Laboratory who studies matter in its most extreme forms—from roiling magma in the center of our planet to the conditions inside the heart of distant stars. During

Fusion Energy Week, Gleason discussed the current state of fusion energy research and how SLAC is helping push the field forward.

What is fusion energy?

Fusion is at the heart of every star. The tremendous pressure and temperature at the center of a star fuses atoms together, creating many of the elements you see on the periodic table and generating an immense amount of energy.

Fusion is exciting, because it could provide unlimited energy to our power grid. We're trying to replicate fusion energy here on Earth, though it's a tremendous challenge for science and engineering.

Have we ever been able to replicate fusion in a lab?

Fusion has been at the forefront of scientific inquiry for many decades, but it wasn't until December 2022 that we reached an incredible watershed moment in fusion research. Using a technique called inertial fusion energy, or IFE, researchers at Lawrence Livermore National Laboratory's National Ignition Facility (NIF) focused 192 individual lasers on a fuel "target"—about the size of a pea—made of deuterium and tritium.

These lasers applied a tremendous force onto the target, and it imploded into a burning plasma. The deuterium and tritium atoms fused together, generating helium and a neutron and producing more energy from the reaction than was used to create it. For less than a trillionth of a second, researchers created the center of a star on Earth. After more than 50 years of fusion research, the world finally achieved net energy gain.

That's incredible, but—a trillionth of a second? That seems pretty short.

Very short! The idea is that this process—this burning plasma—can be repeated many times per second, driven by a series of laser shots that create a source of power. Think of it like a car engine: A spark (the laser) ignites the fuel (the fusion fuel target), which only burns for a short time, but repeated cycles of ignition and burning drive sustained power. In the case of inertial fusion energy, this would be the equivalent of a one million horsepower engine.

Right now, the NIF produces one or two shots each day. We're trying to go from one shot each day to multiple shots each second. If we can orchestrate these implosions multiple times a second, we can generate a continuous flow of power—and do so in a way that is safe, carbon-free and at a scale that meets the long-term energy demands of our world.

Now that we know fusion is possible on Earth, how far are we from having this unlimited energy source on our national power grid?

There are numerous barriers we need to overcome before commercialized fusion energy is a reality. As I said before, we need to move from one laser shot each day to something on the order of 10 shots per second.

High repetition rate is critical. Beyond that, we need to develop the technology to deliver the fuel targets into the fusion chamber, track their movements and engage them with lasers at the same rate—10 times per second. The third challenge is designing the targets themselves to ensure they fuse and generate energy every single time.

Right now, our understanding of the physics and materials science of these targets is at an early stage—a very low technology readiness level.

Even more foundationally, we need people. We need to be training up experts at every level—from power plant operators, technicians and electricians to Ph.D.s in science and engineering. These are good jobs that can be domestically sourced. We need to be educating the workforce, at all levels, for power plant design and operation.

What is SLAC doing to address these challenges?

SLAC is furthering fusion energy science and technology in several ways, including in partnership with other national labs, universities and private companies.

One significant opportunity is the challenge of high repetition rates—moving from one laser shot per day to 10 shots every second. SLAC has years of experience on exactly this topic. We are home to the only domestic X-ray free electron laser, the Linac Coherent Light Source (LCLS), and its cutting-edge experimental end stations. We're leveraging these facilities to build up the capabilities for high-repetition laser-target interactions.

The challenge is getting everything just right and at the right scale for fusion. For each laser-target interaction, the target must be exactly positioned and its movements continuously tracked and predicted with a high degree of accuracy. The optics—the mirrors and lenses—must be precisely adjusted to direct the lasers.

Achieving this perfection at a system scale, like that of a power plant, is tremendously difficult, and demands meticulous, step-by-step testing to get all the bugs and kinks worked out.

Because of SLAC's unique expertise and facilities—for instance, operating high-repetition rate facilities like LCLS which require the synchronization of many systems—we are well-positioned to tackle that complexity.

If we want to build a foundational understanding, develop best practices and do mid-scale demonstrations to tune the design for high repetition rates, there really is no better place. We already have all the pieces in the same location here at SLAC.

What about other areas, like target tracking and target material design?

LCLS provides X-ray pulses to advanced end stations, including the Matter in Extreme Conditions (MEC) and Megaelectronvolt Ultrafast Electron Diffraction (MeV-UED) end stations. Both MEC and MeV-UED have their own unique superpowers that help us advance fusion technologies.

At MEC, we combine ultrafast X-ray pulses from LCLS with ultrahigh-power lasers. This allows us to replicate the complexities of targets under extreme conditions, like those of a fusion target chamber, and to test target delivery and tracking systems. We are building up advanced systems and diagnostics, then training people to develop the skills they need to orchestrate repeated, consistent target delivery.

MEC also helps us study materials for fusion fuel targets. For example, one potential fusion fuel target is a porous foam—like the sponge on your kitchen sink—that can absorb liquid fuels, such as deuterium and tritium. When a powerful laser is directed at the foam capsule, the outer layer forms plasma, generating a shockwave that compresses the sample and initiates the fusion process. Cool, right?

With MEC, we can replicate this process and watch the foam's response in real-time, visualizing how the fuel capsule material behaves under these extreme conditions. This data feeds into our computational models and simulations, allowing us to make more accurate predictions about how all these systems might come together in a power plant.

And what is the MeV-UED's superpower?

We use the MeV-UED facility to study the structural materials needed for building a fusion target chamber. These materials will endure harsh conditions, including radiation and high neutron flux, that can degrade them over time. MeV-UED helps us understand how different materials will behave in those conditions and identify the most durable options.

Looks like some great headway on the technical challenges. But what about building up a workforce?

SLAC is a destination for students who are excited to work in fusion. We have the large-scale facilities onsite, paired with a High Energy Density Science program where students

learn from Stanford faculty across disciplines. Beyond that, we're the headquarters for LaserNetUS, a collaborative network of laser facilities across the U.S. and Canada.

This partnership allows students and postdocs to conduct experiments, connect with the commercial sector and learn from experts across the continent. We're both a home base and a launch pad for careers in fusion energy.

You mentioned that fusion power plants will need a workforce beyond scientists and engineers. How can we build up that workforce across the nation?

I'm co-leading a new initiative called Inertial Fusion Energy 50, or IFE 50. As part of the Department of Energy's IFE-STAR Ecosystem, IFE 50 aims to make connections with every single state in the U.S. We want to generate a community network across academia, national labs and private industry, laying the groundwork for strong American jobs that offer real value to each state

Is there a local vendor that can supply raw materials? Is there interest in starting a new trade school program that will support the electrical, mechanical and HVAC systems needed at power plants? We want to start having those conversations now, so that when the technology is ready, the American workforce is, too.

Why is this work so important to you?

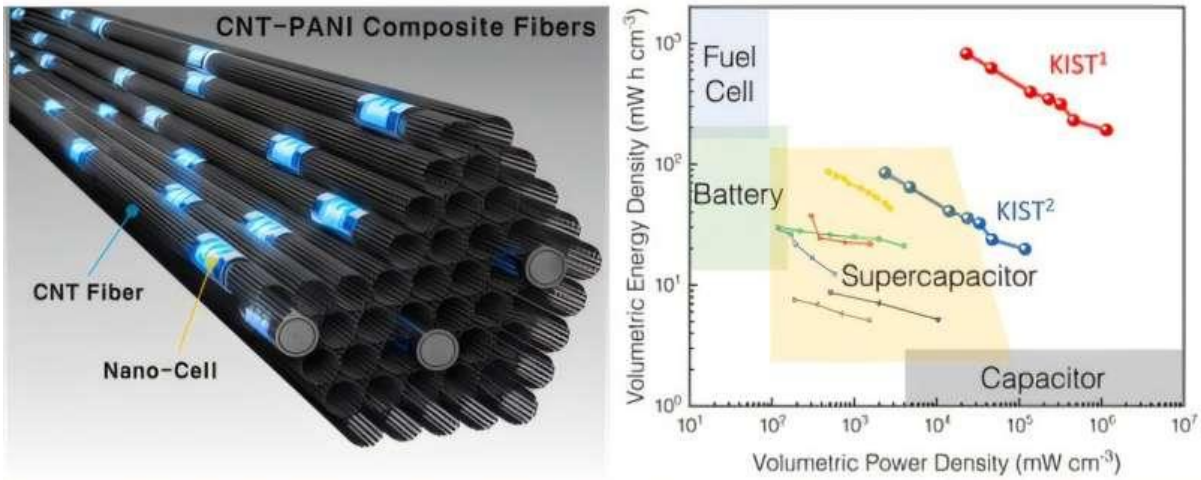
I am so excited to come into SLAC every day. We do such incredible work here, leveraging our unique facilities and our people. And you know, it doesn't stop at fusion energy—our work translates to many areas of energy and security that help make our country strong and secure. We are so proud of what we do.

Provided by SLAC National Accelerator Laboratory

MAY 9, 2025

Scientists develop next-gen energy storage technologies that enable high power and capacity simultaneously

by National Research Council of Science and Technology



(Left) Schematic illustration of a composite of CNTs and PANIs. It shows that the covalently bonded PANIs are evenly distributed among the CNTs and that each PANI can act as a nanoscale cell.(Right) The composite fiber fabricated based on these characteristics shows excellent power and energy density at the simultaneously, exceeding the characteristics of general supercapacitors. (*KIST1 is the value calculated by the weight of only PANI, and KIST2 is the value calculated by the weight of the fiber.). Credit: Korea Institute of Science and Technology (KIST)

A research team has developed a high-performance supercapacitor that is expected to become the next generation of energy storage devices. With details published in the journal *Composites Part B: Engineering*, the technology developed by the researchers overcomes the limitations of existing supercapacitors by utilizing an innovative fiber structure composed of single-walled carbon nanotubes (CNTs) and the conductive polymer polyaniline (PANI).

Compared to conventional batteries, supercapacitors offer faster charging and higher power density, with less degradation over tens of thousands of charge and discharge cycles. However, their relatively low energy density limits their use over long periods of time, which has limited their use in practical applications such as electric vehicles and drones.

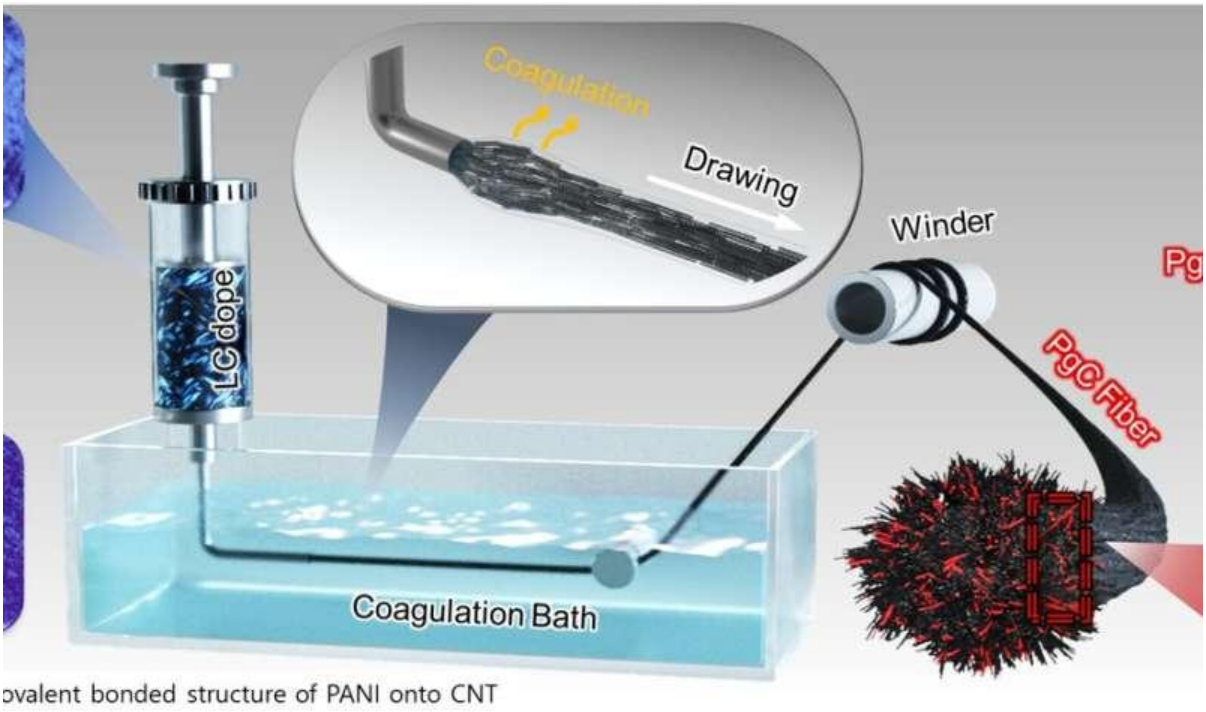
Researchers led by Dr. Bon-Cheol Ku and Dr. Seo Gyun Kim of the Carbon Composite Materials Research Center at the Korea Institute of Science and Technology (KIST) and Professor Yuanzhe Piao of Seoul National University (SNU), uniformly chemically bonded

single-walled carbon nanotubes (CNTs), which are highly conductive, with polyaniline (PANI), which is processable and inexpensive, at the nanoscale.

This creates a sophisticated fiber structure that simultaneously enhances the flow of electrons and ions, resulting in a supercapacitor that can store more energy while releasing it at a faster rate.

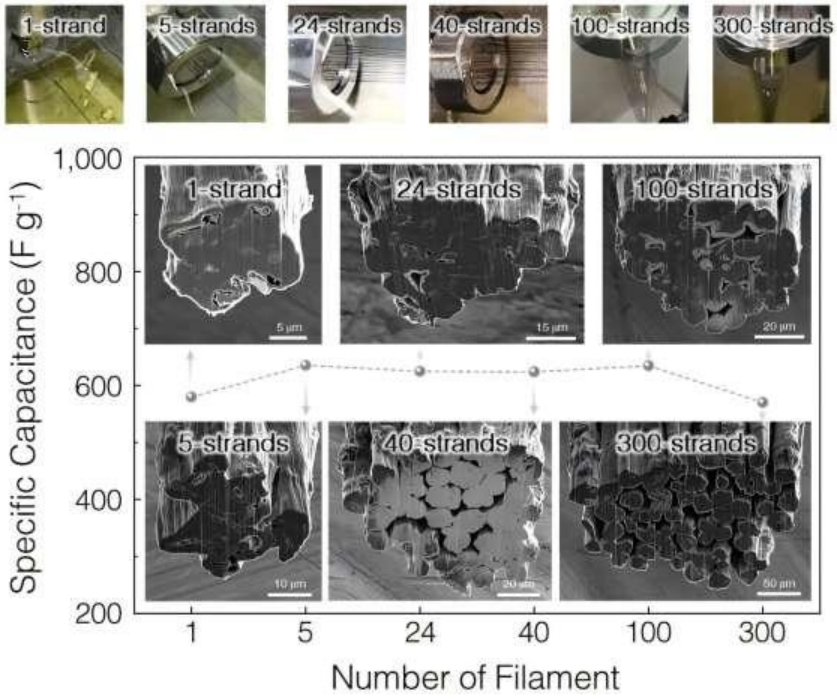
The developed supercapacitor has been shown to maintain stable performance even after more than 100,000 charge and discharge tests and is durable even in high-voltage environments. Thanks to these characteristics, the technology can be utilized as a replacement or complement to existing battery systems. In electric vehicles, for example, it can provide efficient power delivery with fast charging to improve both range and performance.

Other applications, such as drones and robots, could benefit from increased operational time and greater reliability. In addition, the developed composite fiber (CNT-PANI) has high mechanical flexibility, so it can be rolled and folded, enabling it to be applied to next-generation electronic devices such as wearable devices.



ɔvalent bonded structure of PANI onto CNT

- A schematic of the overall process by which PANI manufactures composite fibers: (from left to right) forming a liquid crystal phase based on carbon nanotubes, spinning it into a coagulation bath, solidifying it, and stretching it. The final resulted fiber has a structure with an even distribution of PANI. Credit: Korea Institute of Science and Technology (KIST)



- To see the commercialization potential of composite fiber capacitors, a mass manufacturing process was introduced. Fiber bundles ranging from one-stranded fibers to 300-stranded fibers were produced through the mass production process, and it can be seen that the specific capacitance is well maintained without decreasing because PANI acts as a nanocell inside. Credit: Korea Institute of Science and Technology (KIST)

Another major achievement of the research is the reduction of production costs and the possibility of mass production.

Despite their excellent properties, single-walled carbon nanotubes (CNTs) have been difficult to commercialize due to their high production costs, but the researchers solved this problem by compounding them with the low-cost conductive polymer polyaniline (PANI).

Furthermore, they have laid the foundation for mass production through a simple process, and recently succeeded in developing film-like structures based on this technology, further advancing commercialization. In the future, it will be utilized as a key enabling technology for the transition to a carbon-neutral society across various industries, such as electric vehicles, robots, drones, and wearable devices.

"This technology overcomes the shortcomings of supercapacitors by using single-walled carbon nanotubes and conductive polymers," said Dr. Bon-Cheol Ku of KIST.

"We will continue to develop and industrialize ultra-high-performance carbon fibers based on carbon nanotubes."

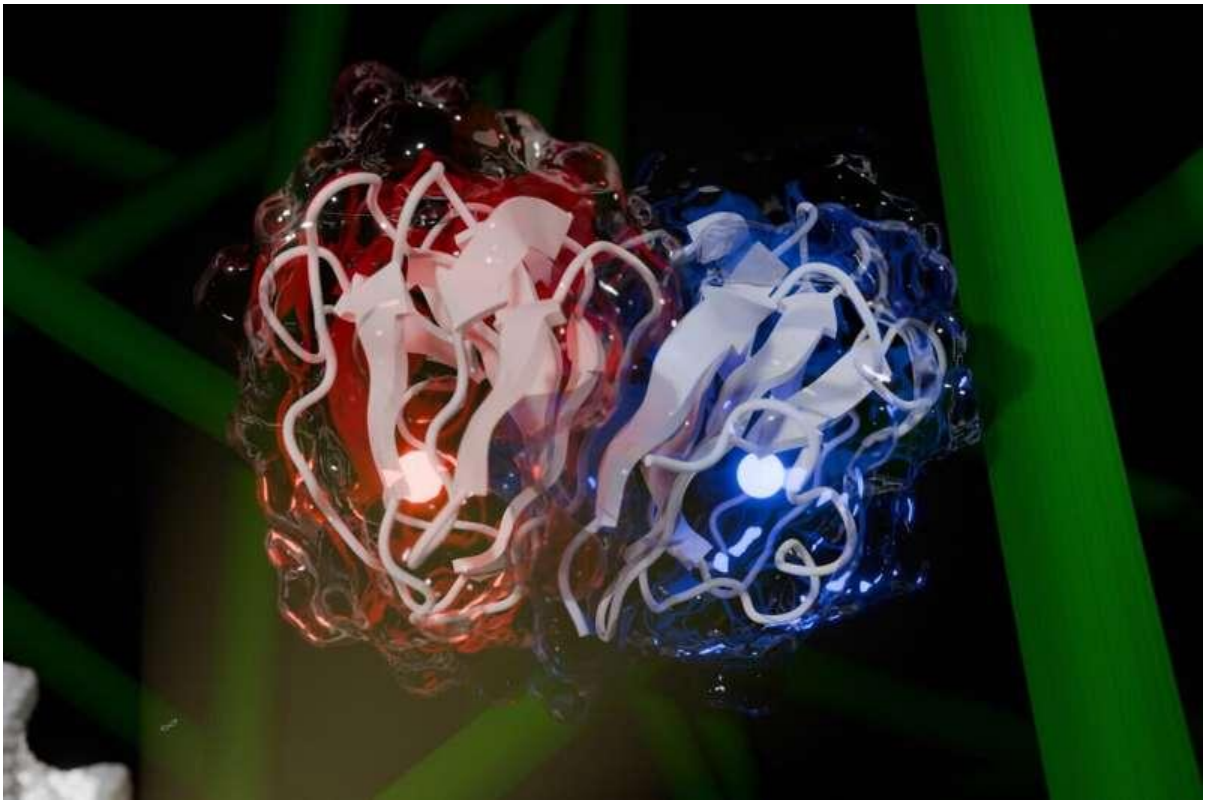
More information: Dongju Lee et al, Nanocell-structured carbon nanotube composite fibers for ultrahigh energy and power density supercapacitors, *Composites Part B: Engineering* (2025). DOI: 10.1016/j.compositesb.2025.112179

Provided by National Research Council of Science and Technology

MAY 9, 2025

Natural enzyme capable of cleaving cellulose could transform biofuel production

by José Tadeu Arantes, FAPESP



The dimeric structure of the CelOCE enzyme acting on cellulose fibers, represented by the green sticks. Credit: Mario Murakami/CNPEM

The deconstruction of cellulose is essential for the conversion of biomass into fuels and chemicals. But cellulose, the most abundant renewable polymer on the planet, is extremely recalcitrant to biological depolymerization. Although composed entirely of glucose units, its crystalline microfibrillar structure and association with lignin and hemicelluloses in plant cell walls make it highly resistant to degradation.

As a result, its degradation in nature is slow and requires complex enzymatic systems. The deconstruction of cellulose, which could, among other things, significantly increase the

production of ethanol from sugarcane, has been a major technological challenge for decades.

Researchers from the Brazilian Center for Research in Energy and Materials (CNPEM), in partnership with colleagues from other institutions in Brazil and abroad, have just obtained an enzyme that could revolutionize the process of deconstructing cellulose, allowing, among other technological applications, the large-scale production of so-called second-generation ethanol, derived from agro-industrial waste such as sugarcane bagasse and corn straw. The study was published in the journal *Nature*.

"We've identified a metalloenzyme that enhances cellulose conversion through a previously unknown mechanism of substrate binding and oxidative cleavage. This discovery establishes a new frontier in redox biochemistry for the depolymerization of plant biomass, with broad implications for biotechnology," said Mário Murakami, head of the CNPEM biocatalysis and synthetic biology research group and coordinator of the study.

The newly discovered enzyme was named CelOCE, which stands for cellulose oxidative cleaving enzyme. It cleaves cellulose using an unprecedented mechanism, allowing other enzymes in the enzyme cocktail to continue their work and convert the fragments into sugar.

"To use a comparison, the recalcitrance of the crystalline structure of cellulose stems from a series of locks that classical enzymes cannot open. CelOCE opens these locks, allowing other enzymes to do the conversion. Its role isn't to produce the final product but to make the cellulose accessible. There's a synergy, the potentiation of the action of other enzymes by the action of CelOCE," states Murakami.

Paradigm shift

According to the researcher, the addition of monooxygenases to the enzyme cocktail about two decades ago was the first revolution. These enzymes directly oxidize the glycosidic bonds in cellulose, facilitating the action of other enzymes. It was the first time that redox biochemistry was used as a microbial strategy to overcome the recalcitrance of cellulose biomass. And that set a paradigm.

Everything that was discovered at that time was based on monooxygenases. Now, for the first time, that paradigm has been broken with the discovery of CelOCE, which is not a monooxygenase and provides a much more significant result.

"If we add a monooxygenase to the enzyme cocktail, the increase is X. If we add CelOCE, we get 2X: twice as much. We've changed the paradigm of cellulose deconstruction by the microbial route. We thought that monooxygenases were nature's only redox solution for dealing with the recalcitrance of cellulose.

"But we discovered that nature had also found another, even better strategy based on a minimalist structural framework that could be redesigned for other applications, such as environmental bioremediation," says Murakami.

The researcher explains that CelOCE recognizes the end of the cellulose fiber, attaches itself to it and cleaves it oxidatively. In doing so, it disrupts the stability of the crystalline structure, making it more accessible to the classical enzymes, the glycoside hydrolases. A very important fact is that CelOCE is a dimer, consisting of two identical subunits. While one subunit "sits" on the cellulose, the other one is free and can perform a secondary oxidase activity, generating the necessary co-substrate for the biocatalytic reaction.

"This is really very innovative because monooxygenases depend on an external source of peroxide, whereas CelOCE produces its own peroxide. It's self-sufficient, a complete catalytic machine. Its quaternary structural organization makes it possible for the site that isn't engaged on cellulose to act as its peroxide generator.

"This is a huge advantage because peroxide is a highly reactive radical. It reacts with a lot of things. It's very difficult to control. That's why, on an industrial scale, adding peroxides to the process is a major technological challenge. With CelOCE, the problem is eliminated. It produces the peroxide it needs in situ," emphasizes Murakami.

CelOCE is a metalloenzyme: This is its exact classification because it has a copper atom embedded in its molecular structure, which itself acts as a catalytic center. It was not created in a laboratory but discovered in nature. However, to get to it, the researchers had to mobilize a formidable amount of science and equipment.

"We started with samples of soil covered with sugarcane bagasse that had been stored for decades in an area adjacent to a biorefinery in the state of São Paulo.

"In these samples, we identified a microbial community highly specialized in the degradation of plant biomass, using a multidisciplinary approach that included metagenomics, proteomics, carbohydrate enzymology by chromatographic, colorimetric and mass spectrometric methods, fourth-generation synchrotron-based X-ray diffraction, fluorescence and absorption spectroscopies, site-directed mutagenesis, genetic engineering of filamentous fungi using CRISPR/Cas and experiments in 65-liter and 300-liter pilot plant bioreactors.

"We went from biodiversity exploration to mechanism elucidation to an industrially relevant scale in a pilot plant with the possibility of immediate real-world application," says Murakami.

The researcher emphasizes that this was not a laboratory bench result that still needs to be validated before it can be used on an industrial scale. The proof of concept has already been demonstrated on a pilot scale, and the newly discovered enzyme can be immediately incorporated into the production process—which is extremely relevant for Brazil, as a major producer of biofuels, and for the world, in a context of urgent energy transition due to the climate crisis.

Brazil has the only two biorefineries in the world capable of producing biofuels from cellulose on a commercial scale. The trend is for these biorefineries to multiply here and be replicated in other countries. One of the biggest challenges so far has been the

deconstruction of cellulose biomass: how to break it down and convert it into sugar. CelOCE is expected to significantly increase the efficiency of this process.

"Currently, efficiency is in the 60% to 70% range, and in some cases it can reach 80%. That means that a lot is still not being used. Any increase in yield means a lot, because we're talking about hundreds of millions of tons of waste being converted," Murakami argues. He adds that it is not just about increasing the production of ethanol for vehicles, but also for other products, such as aviation biofuel.

More information: Clelton A. Santos et al, A metagenomic 'dark matter' enzyme catalyses oxidative cellulose conversion, *Nature* (2025). DOI: 10.1038/s41586-024-08553-z
Journal information: Nature
Provided by FAPESP

MAY 22, 2025

Where Switzerland's power will come from in 2050

by Christoph Elhardt, ETH Zurich edited by Lisa Lock, reviewed by Andrew Zinin

To achieve its energy targets, Switzerland must massively expand photovoltaics and wind energy. Wind turbines and solar panels on Mont-Soleil in Saint-Imier. Credit: Valentin Flauraud /Keystone
By 2050, the aim is for Switzerland's energy system to be decarbonized and no longer reliant on nuclear power. How this can be achieved and the costs of doing so are set out in a new report by a Swiss research consortium involving researchers from ETH Zurich, the universities of Geneva and Bern, EPFL, WSL, and ZHAW.

The goal is for Switzerland's energy supply to be carbon-neutral by 2050. This will require the electrification of transport, heating and industry, raising the annual electricity demand from the current level of 56 terawatt-hours (TWh) to around 75 TWh by 2050. At the same time, the contribution of 23 TWh from the Swiss nuclear power plants will need to be replaced.

A new report by the Sweet-consortium external pageEDGE sets out the first comprehensive investigation of how the energy transition can be implemented by 2050. The report encompasses multiple studies, which were carried out with the participation of researchers from ETH Zurich, EPFL and WSL, the Universities of Geneva and Bern, and the ZHAW.

Significantly more electricity from wind and sun

On 9 June 2024, 69% of Swiss voters approved the Electricity Act, which stipulates that, by 2050, Switzerland is to meet some 60% of its electricity demand (45 TWh per year) from new renewable energy sources such as photovoltaics, wind energy or biomass.

In the first study of the report, the researchers established that there are various routes by which Switzerland can reach the 45 TWh target. However, this will require massive expansion of photovoltaics and wind energy. Of the 45 TWh of electricity, an average of some 28 TWh would come from photovoltaic systems, 13 TWh from wind turbines, and the rest from biomass.

On average, the installed capacity of photovoltaics in Switzerland would need to grow from 6.4 gigawatts (GW) today to some 26.8 GW in 2050—a four-fold increase. In the case of wind energy, which is vital to electricity generation in winter, a much bigger expansion would be needed. Specifically, capacity would need to increase from an average of 0.1 GW today to some 8.4 GW in 2050—over 80 times the current figure.

"This major expansion of photovoltaics and wind energy by 2050 is almost inconceivable without effective subsidies," says Giovanni Sansavini, Professor of Reliability and Risk Engineering at ETH Zurich and one of the study's co-authors.

Limiting net imports would be expensive

The Electricity Act also stipulates that electricity net imports in winter must not exceed 5 TWh. If implemented strictly, this rule will necessitate significantly more home-grown power.

Indeed, according to the researchers' models, there will be a need for 80% more capacity from wind farms, 11% more capacity from gas-fired power stations, and 10% more capacity from solar power plants. Moreover, the costs of supplying electricity, which are principally made up of investment and operating costs, could increase by a fifth, and the price of electricity could more than double.

Credit: ETH Zurich

Reliance on the European electricity market

In future, the EU could reserve 70% of its network capacity for trade between EU member states. The researchers therefore also model how a 70% reduction of cross-border electricity trading volume would impact the electricity mix and the electricity supply costs.

They conclude that the installed capacity of wind turbines in Switzerland would need to increase by a further 20% in order to absorb a 70% reduction of cross-border electricity trading volume. Furthermore, the electricity supply costs would increase by 8% in such a scenario.

"Our results provide an impressive demonstration of how important it is for Switzerland to be seamlessly integrated into the European electricity market. Without integration, not only the cost of supplying electricity but also the electricity itself will become more expensive. It's

also clear that we need more wind turbines," explains Ambra Van Liedekerke, a doctoral student in Sansavini's group and one of the study's co-authors.

According to a representative survey conducted by the Edge research consortium, around 60% of the Swiss population are in favor of closer cooperation with the EU in order to secure energy supplies. At the same time, however, around 70% of the approximately 2,000 people surveyed said that Switzerland should be independent in energy matters and that electricity imports are unpopular compared to domestic energy sources.

Swiss investments flow out of the country

The results of another study in the report reveal just how closely the Swiss energy system is interconnected financially with Europe: over half of all annual investments by Swiss electricity suppliers and financial investors in renewable utility-scale energy projects now flow to other European countries. These projects are powerplants with a capacity of over one megawatt. Only 1% of these investments remain in Switzerland.

The most money goes to Germany ($177 million a year on average), France ($112 million a year on average) and Italy ($43 million a year on average), and Swiss backers additionally invest $644 million outside of Europe. It is striking that almost 60% of this Swiss money goes towards wind energy projects.

"As it seems, investors tend to finance renewable energy projects in foreign countries that they couldn't implement on the same scale in Switzerland. In this way, Switzerland is contributing to the energy transition beyond its own borders," explains Bjarne Steffen, head of the Climate Finance and Policy Group at ETH Zurich and one of the co-authors of the report.

The cost of net zero for Switzerland

A third study from the EDGE report models how expensive it could be for the Swiss population to achieve the net-zero target in the Paris Climate Agreement. The researchers assume that fossil energy prices and the production costs of many goods will rise by 2050 as a result of carbon taxes and emissions trading. This would also make many everyday products and services such as housing, energy, but also food and mobility more expensive.

Swiss households would be affected by lower income and higher prices between 2020 and 2050 and could consume less as a result. The extent of this loss depends on climate protection efforts abroad. If only Europe becomes climate neutral by 2050, the transition could cost the average Swiss household 0.63% of its consumption per year.

However, if all OECD countries achieve net zero by 2050, China by 2060 and the rest of the world by 2070, the additional slowdown of economic growth could raise the cost to 0.75% of the annual consumption of a Swiss household.

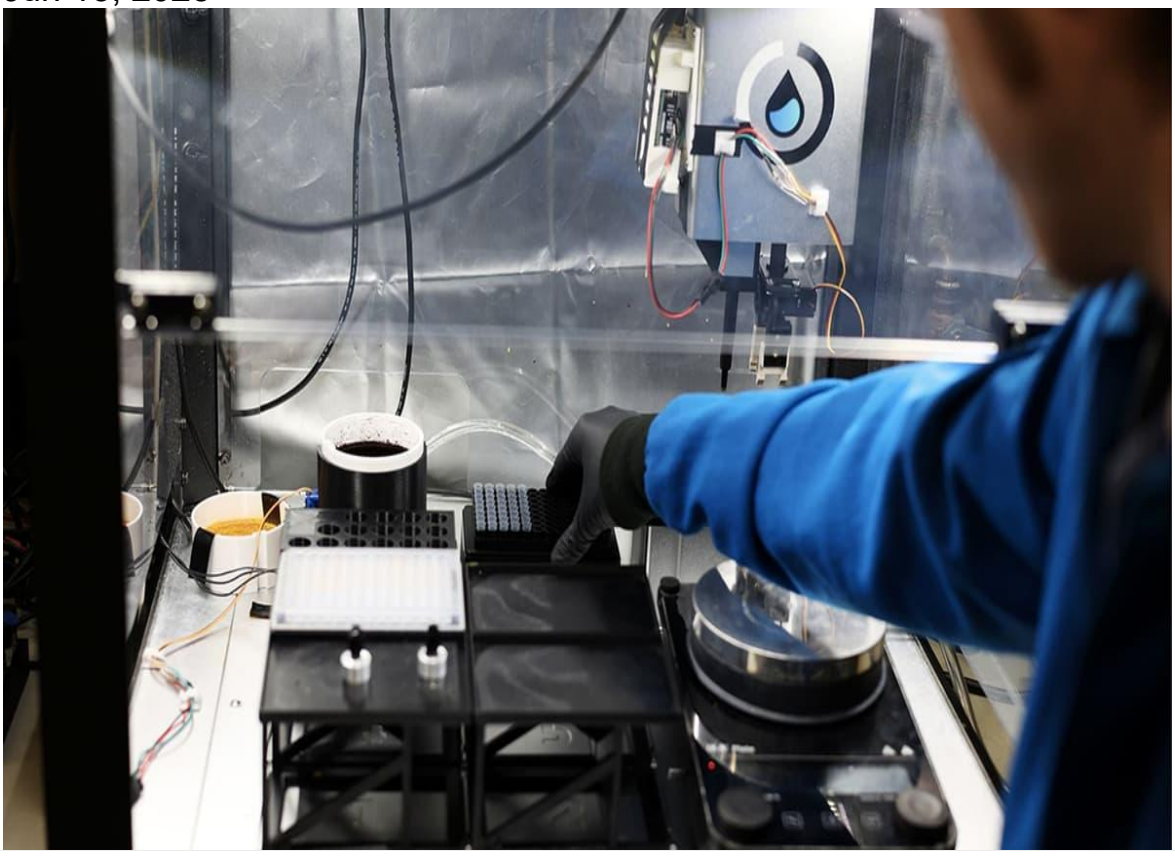
The fact that these costs are not higher depends on whether Switzerland can offset its emissions abroad. If that is not possible, the cost could rise to 1% per year and household.

"When interpreting these costs, it's always important to bear in mind that the costs of unchecked CO_2 emissions would probably be much higher," says Philippe Thalmann, Professor of Economics at EPFL and one of the report's co-authors.

More information: Renewable Energy Outlook II for Switzerland. DOI: 10.3929/ethz-b-000735887
Provided by ETH Zurich

Wafer-thin, shapeshifting perovskites can help make efficient renewable energy sources

The perovskites can be manipulated easily at the molecular level.
Jun 13, 2025



The wafer-thin perovskites' optical properties shift with temperature changes.

Scientists have revealed that in a recent experiment, the Ruddlesden-Popper (RP) metal-halide hybrid emerged as a promising class of two-dimensional (2D) materials for optoelectronics and thermal energy storage in a recent experiment.

A type of layered material made from alternating sheets of inorganic and organic components, Ruddlesden-Popper perovskites are potentially ideal for several applications, including light-emitting diodes (LEDs), thermal energy storage, and solar-panel technology.

Researchers also revealed that metal-halide perovskites are promising materials for a wide range of optoelectronic applications. However, integrating them into devices is challenging because of the variety of dynamic processes they undergo near room temperature. They stressed that structural phase transitions in these materials influence their optical properties.

Water and perovskites have multiple solid states with different properties

In a recent study, researchers from the University of Utah utilized temperature-dependent absorption and emission spectroscopy, as well as X-ray diffraction, to study the phase transition behaviors of perovskites.

Researchers highlighted that a phase transition is a discrete change from one state of matter to another (such as ice to liquid water). Some substances, including water and perovskites, have multiple solid states with different properties.

The experiment performed at Bischak Lab housed in the Department of Chemistry demonstrated a connection between phase transitions and the material's emissive properties.

Interplay of the organic and inorganic alters material's properties

This introduces a form of dynamic control, or tunability, that offers multiple benefits for technological applications. Specifically, because perovskites contain both organic and inorganic components, the organic layers undergo phase transitions that influence the structure of the inorganic layers. The interplay of the organic and inorganic layers drastically alters the material's properties, according to researchers.

"There are these almost greasy chains that kind of crystallize together. When you hit a certain temperature, those will essentially melt and become more disordered," said Assistant Professor Connor Bischak, senior author of the new study.

“The melting process influences the structure of the inorganic component, which controls how much light is emitted from the material and its wavelength.”

Bischak also underlined that the perovskites can be manipulated easily at the molecular level. The emission wavelength can be tuned from ultraviolet up to near-infrared.

Optical properties shift with temperature changes

Researchers stressed that the wafer-thin perovskites’ optical properties shift with temperature changes.

“We also observe temperature-dependent, continuous changes in the band gap driven by subtle octahedral distortions in the inorganic layers. Overall, our findings reveal how structural changes at phase transitions influence the optoelectronic properties of 2D perovskites,” said researchers in the study published in the journal *Matter.*

Moreover, perovskites offer powerful advantages for next-generation solar cell technology. While silicon has long been the standard material for solar cells, it faces limitations due to its energy-intensive manufacturing process and ongoing supply chain issues. In contrast, perovskites are solution-processable materials, as per a press release.

“What that means is you basically dissolve all these precursor chemicals in a solvent, and then you can make your solar cell almost like printing with ink,” added Bischak.

RECOMMENDED ARTICLES
“It produces an efficient solar cell material that’s better than silicon.”

Perovskite materials offer a promising path for cleaner and more adaptable energy solutions. Their unique tunability, ease of processing, and compatibility with current technologies make them a strong candidate for innovation in energy solutio