

of the body on which they were used (from pot labels with instructions such as “substance for the head” or “for making beautiful the skin”).

For the analyses of organic residues, the authors chose 31 out of 121 vessels from the embalming area that were the most clearly labelled, together with 4 other samples that came from burial chambers. The materials identified included: oils or tars of juniper, cypress and cedar, and various resins including those from *Pistacia* trees, animal fats, beeswax and plant oils, almost all of which were identified previously in mummies^{7–10}. Rageot and colleagues’ most notable identifications were those of two resins, dammar and elemi, which have not been identified in excavations anywhere in Egypt before, and of bitumen from the Dead Sea.

All the resins were from the Near East Levant region (the general area of what is now Lebanon and Syria), except for dammar and elemi, which probably originate from rainforests in Asia or, a less likely possibility, Africa. These resins provide fresh evidence for long-distance trade networks, and raise the question of how and when the Egyptians learnt of these resins and obtained a specialized understanding of their properties and relevance to mummification.

Although bitumen has long been associated with mummification, it was chemically detected in mummies only a few years ago¹². Notably, Rageot *et al.* found bitumen only in the burial-chamber vessels. Perhaps it was not used in the initial stages of embalming, but only during the final rites, and it might have also had a role in the anointing of funerary objects in addition to (or rather than) the mummy¹³.

Analyses on pots labelled *antiu* and *sefet*, traditionally identified as myrrh and oil, respectively, show that the former consists of a mixture of oil or tar of cedar, juniper and cypress and animal fat. The recipe for the latter was more varied: some vessels contained animal fats mixed with oil or tar of juniper and cypress, and one had ruminant fat and elemi. Although the recipes for *antiu* and *sefet* are similar, they are not identical. Further work might explain which properties of these substances the embalmers valued, and why they blended them in a particular fashion to create these mixtures for use on different parts of the body.

Rageot and colleagues’ work provides an important step forward in our understanding of ancient Egyptian embalming materials and methods. These analyses can be further built on if the team can ‘mummy-truth’ (verify) the materials’ prescribed use on the mummies themselves, and can see how or whether the mixtures relate to those listed in the translated embalming manual³. Similar work should be carried out on other mummies to elucidate evolving mummification methods, to examine geographical variations, to assess the socio-economic status of the deceased

and to understand the diverse trade routes that supplied embalmers for more than 3,000 years.

Salima Ikram is in the Department of Sociology, Egyptology and Anthropology, The American University in Cairo, New Cairo 11835, Egypt.
e-mail: salima@aucegypt.edu

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Catalysis

Catalysts light a path to sustainable chemistry

Emiliano Cortés

A light-activated ‘plasmonic’ catalyst, made from abundant elements, produces as much hydrogen from ammonia as do the most-used heat-activated catalysts based on a rarer element, suggesting a strategy for sustainable chemical production.

Future sustainable industrial processes for synthesizing chemicals should avoid burning fossil fuels, produce no carbon emissions and be cheaper than current processes – industry will not adopt sustainable processes that are more costly than existing ones. Writing in *Science*, Yuan *et al.*¹ report that a plasmonic catalyst – a type of light-activated catalyst – based on abundantly available copper and iron can be used to produce hydrogen gas, a green fuel, from ammonia (NH₃). This

“The observation that an almost inactive thermal catalyst can become a top performer under illumination is striking.”

light-powered process generates hydrogen as efficiently as does a widely used heat-driven catalyst based on ruthenium, a much scarcer element. The findings reveal opportunities for plasmonic catalysts in sustainable industrial processes, and might help to establish the wide-scale use of light to power chemical reactions. Moreover, it suggests that catalysts based on Earth-abundant elements might finally emerge for use in a

broad range of industrial applications.

Of all the industrial sectors, the chemical industry is the largest consumer of energy and the third-largest direct producer of carbon dioxide emissions (see go.nature.com/3r4ufgm). In 2021, the global chemical industry emitted 925 megatonnes of CO₂. About 75% of these emissions came from fossil-fuel combustion, which is used to produce the high temperatures and pressures required for most industrial chemical reactions.

A long-standing strategy for mitigating these issues is to develop new catalysts for industrial reactions, to reduce the overall energy input. Precious metals are currently the preferred catalysts for most chemical reactions. However, such metals are expensive and are not abundant in Earth’s crust, making them unsustainable for long-term industrial use. The challenge is therefore to find alternative Earth-abundant catalysts.

Another challenge for the chemical industry is to replace fossil fuels with green fuels, such as hydrogen, that (ideally) can be obtained sustainably and produce no CO₂ on combustion. A future hydrogen-based economy will require methods for the long-term, large-scale storage and transport of hydrogen, a highly reactive gas. One approach is to react hydrogen with nitrogen to produce ammonia

From the archive

A long-awaited acknowledgement of Faraday's work on electromagnetism, and the case for studying parasitic worms.

50 years ago

More than 105 years after his death, the Royal Institution has finally paid tribute to Michael Faraday. Earlier this week the Queen, the Royal Institution's patron, opened a museum, an archive room and a refurbished laboratory, all bearing Faraday's name. Professor Sir George Porter, the institution's director, repeated Faraday's chief experiments on electricity — including, with commendable energy, a hand-driven demonstration of electromagnetic induction with a light bulb, a coil and an iron bar — and the Queen unveiled a plaque on the floor below, initiating the curtain motor by an impulse from the original iron ring used by Faraday when he discovered electromagnetic induction. The ring worked, the curtain drew back and everyone applauded.

From *Nature* 9 February 1973

150 years ago

The migration of helminths is one of the most interesting discoveries of modern zoology. These worms, generally parasitic, must often, in order to complete their growth, pass from one animal into another. This passage is of course accomplished by chance, as when one animal devours the whole or part of another, in which the helminth at a certain stage may be imbedded ... Should any one ask of what service are such curious, difficult, and apparently useless researches, it could be replied that many illnesses, some of them mortal, arise from parasites that attack certain parts of our body (the intestines, the liver, &c.); and every advance in our knowledge of the habits of those beings is a service rendered, not only to science, but also to humanity.

From *Nature* 6 February 1873

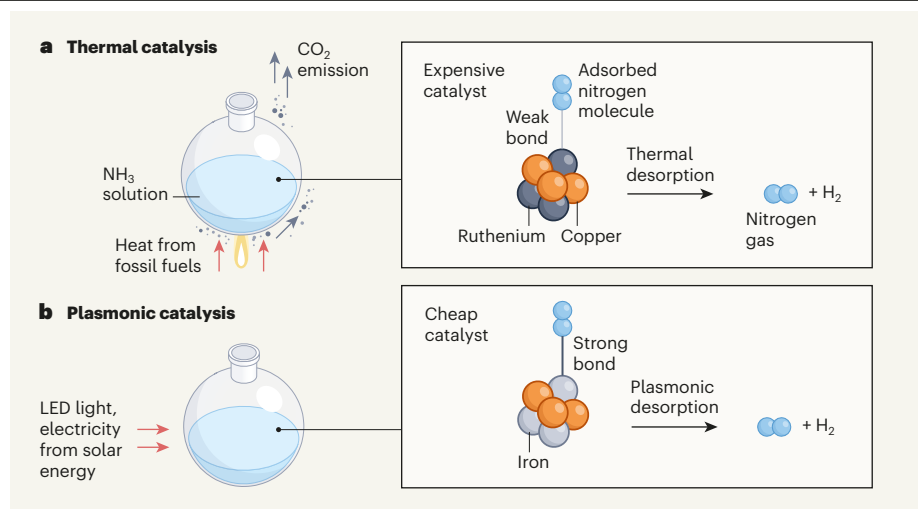


Figure 1 | Catalytic processes for the decomposition of ammonia. **a**, Hydrogen (H_2) and nitrogen (N_2) gases can be produced from ammonia (NH_3) using ruthenium-containing catalysts (shown here is a copper–ruthenium alloy). The rate-determining step of the reaction is desorption of nitrogen molecules from catalytic ruthenium atoms. This involves breaking of a relatively weak bond using heat, typically produced by burning fossil fuels. However, ruthenium is expensive and fossil-fuel combustion produces carbon dioxide emissions. **b**, Yuan *et al.*¹ report that LED-illuminated copper–iron catalysts are about as active as the best thermally activated ruthenium catalysts. The LED excites the ‘plasmonic’ copper–iron catalyst, facilitating desorption of otherwise strongly bound nitrogen molecules from the iron atoms. Such reactions are potentially much more sustainable than are those in **a**, because iron is much cheaper and more abundant than ruthenium, and the LEDs could be powered by electricity produced from solar energy.

as a storage medium or carrier, which can then be converted back to hydrogen on site when needed.

Ruthenium-based catalysts are currently best at promoting the decomposition of ammonia to produce hydrogen². However, ruthenium is a relatively rare element, found at just 0.00004 parts per million in Earth's crust. Iron is much more abundant, constituting 52,157 parts per million of the crust. However, transition metals such as iron are extremely poor catalysts for the thermal decomposition of ammonia³.

Yuan *et al.* explored whether iron could be used to decompose ammonia through a different type of catalysis, known as plasmonic catalysis⁴. Unlike heat-activated catalysts, in which the entire material is uniformly excited, plasmonic catalysts harvest the energy of light and allocate it to their electrons. These light-energized materials can then promote catalytic processes in molecules adsorbed at their surface. Earth-abundant plasmonic materials, such as copper, aluminium and magnesium, could be particularly useful for the development of sustainable industrial chemistry powered by light.

Desorption of molecules from the catalyst surface is the most energy-consuming step in many chemical reactions. Previous work has shown that light-illuminated plasmonic materials can induce the desorption of molecules bound to catalysts⁵, a process known as desorption induced by electronic transitions (DIET)⁶. It had previously been suggested that DIET from metal surfaces could affect catalytic

reactions only when using high-power pulsed lasers⁷, which would limit its application on an industrial scale. Yuan *et al.* now show that plasmonic materials made of copper and iron can induce molecular desorption under illumination by light-emitting diodes (LEDs) in the ammonia decomposition reaction (Fig. 1).

The authors find that, when the reactions are heated (but not irradiated with light), hydrogen production from ammonia using their copper–iron catalyst is about 300 times lower than it is with an analogous copper–ruthenium catalyst. This is because nitrogen molecules (N_2) produced during the reaction form much stronger bonds to iron than to ruthenium, and therefore desorb much more slowly from the copper–iron catalyst, thus preventing the adsorption of more ammonia molecules at catalytic sites. Indeed, N_2 desorption from the catalyst is the slowest step of the reaction, and therefore determines the overall reaction rate.

By contrast, Yuan *et al.* observe that, under LED illumination at room temperature, the copper–iron catalyst performs about as well as does the copper–ruthenium catalyst under the same conditions, and has comparable activity to the best previously reported thermal catalyst for ammonia decomposition⁸. The observation that an almost inactive thermal catalyst can become a top performer under illumination is striking. The authors carried out further experiments indicating that plasmonic excitation in the copper–iron catalyst activates a non-thermal catalytic pathway involving DIET. This is interesting, because there has been heated debate in the past few years

about whether plasmonic excitation can have a non-thermal role in catalytic reactions^{4,5,9}.

The authors' results demonstrate that the search for plasmonic catalysts based on Earth-abundant metals should not be guided by the many decades of research into thermally driven catalysis. The findings also suggest that this search should focus on cheap catalytic materials from which molecular desorption is hindered – such desorption could be activated by light when the catalysts are combined with a plasmonic material. More specifically, plasmonic DIET triggered by LED illumination of Earth-abundant catalysts is a potential strategy for the development of sustainable industrial chemical processes, because it would avert the need for extensive heating (thereby reducing fuel consumption and potentially achieving zero carbon emissions), while avoiding the use of precious metals.

Indeed, Yuan and co-workers demonstrate that they can produce gram quantities of hydrogen (up to about 18 g per day) using their copper–iron catalyst in a small commercial reactor fitted with LEDs, without heating. This suggests that plasmonic catalysis with LEDs could be a viable strategy for reaching a major goal in this field: the development of a process that enables one kilogram of hydrogen to be made at a cost of US\$1. However, there are many challenges to be overcome, other than lowering the cost, before this approach can be used for the industrial production of green hydrogen.

First, reactors will need to be engineered to ensure that large volumes of reaction solutions can be illuminated uniformly by LEDs. Second, a process for the sustainable, large-scale synthesis of ammonia is required. Currently, ammonia is manufactured by reacting hydrogen with nitrogen, and the hydrogen is obtained from an energy-intensive reaction (steam methane re-forming) that consumes a large amount of fossil fuels. As a result, ammonia production is responsible for the highest fraction of CO₂ emissions from the chemical industry (see go.nature.com/3r4ufgm). Electrically driven processes for ammonia production might solve this problem, but it seems unlikely that sustainable processes for making ammonia and hydrogen will be scaled up for industrial use in the short term.

Nevertheless, Yuan and colleagues' LED-driven method for producing hydrogen from ammonia is a nice proof of concept that could be combined immediately with emerging approaches for the small-scale electrified synthesis of ammonia. The production of small quantities of green hydrogen at some industrial sites might not be too far away.

The third challenge is economic: the cost of using LEDs to drive industrial reactions must be lower than the cost of burning fuels to heat equivalent thermally activated reactions. In this regard, a highly detailed analysis¹⁰ has

shown that sunlight can generate electricity to power LEDs that have electrical-to-optical power efficiencies of about 90% in most cases, thereby providing 'cheap photons' for catalysis. Moreover, the idea of using LEDs (which produce powerful light at a fixed energy) to activate plasmonic catalysts removes the constraints of using sunlight directly – a strategy requiring materials that can absorb the low-intensity, broad spectrum of photons emitted by the Sun. Industrial processes driven by sunlight-powered LEDs could thus become a cheap replacement for some current energy-intensive and high-carbon-emitting processes.

In the next decade, it is to be hoped that the chemical industry will shift towards using more-sustainable processes. In this context, the combination of sunlight-powered LEDs with Earth-abundant catalysts, such as that reported by Yuan *et al.*, might help plasmonic catalysis to transition from the laboratory scale to the industrial scale. We need

more such examples to speed our way to a sustainable future.

Emiliano Cortés is at Nano Institute Munich, Faculty of Physics, Ludwig-Maximilians University of Munich, Munich 80539, Germany. e-mail: emiliano.cortes@lmu.de

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Astronomy

A planetary ring in a surprising place

Matthew M. Hedman

An object in the distant Solar System has been shown to have a ring that is unusually far from its host – prompting speculation about how the ring material has avoided clumping together to form moons. **See p.239**

Planetary rings are disks containing many small chunks of ice and other materials that are in orbit around a larger object¹. Most rings are found within a critical distance of their host, known as the Roche limit, where the gravitational pull of the host prevents this material from accreting into objects. But on page 239, Morgado *et al.*² report the discovery of a ring that doesn't follow this rule: it lies far outside the Roche limit of its host and is thus at odds with our current understanding of how such rings are maintained.

Saturn has the most famous rings system, with rings so large and bright that they can even be seen with small telescopes. But all the other giant planets (Jupiter, Uranus and Neptune) are surrounded by rings too, and these can be seen with sufficiently powerful telescopes, such as the Keck Telescope in Hawaii or the James Webb Space Telescope. Narrow rings have also been found around a few non-planetary bodies in the outer Solar System, such as Chariklo and Haumea^{3,4}. The ring discovered by Morgado and colleagues surrounds an object called Quaoar, which lies beyond Neptune's orbit.

This ring is too small and narrow to be detected directly – even with large telescopes. Instead, the authors used multiple telescopes to monitor the brightness of stars as Quaoar passed in front of them. The ring material around Quaoar caused a temporary dip in the stars' apparent brightness by blocking some of the starlight from reaching the telescopes. And different telescopes observed dips of different shapes and intensities, indicating that the ring's opacity varies along its length. Similar variations have been observed in rings surrounding Saturn⁵ and Neptune⁶. However, the position of Quaoar's ring is very different from that of any comparably opaque ring, and therefore poses a challenge to standard models of planetary rings.

Rings that have sufficient opacity to block detectable amounts of starlight are so dense that their component particles collide with neighbouring particles on timescales comparable to their orbital periods (that is, hours to days). In principle, these collisions could result in the particles sticking together, bouncing off each other or breaking apart – with sticking