



The Catalyst

connecting chemists

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Nuclear Chemistry Team

Writers

Elena Rubini
(Writing Director)

Sofia Schönbauer
(Writing Director)

Paul Amar

Matt Dagwell

Xiaojian Qu

Tara Salal

Louis Weiss



Proofreaders

Reza Ahmad

Nadim Ahmed

Seema Bosor

Janifa Jahir

Neev Lawton

Alia Nathoo



Graphic Editorial Team

Milan Singh
(Graphic Editorial Director)

Rohima Akhtar

Inga Andrzejewska

Anson Cherk

Natalia Koziol

Thais Perros

Anastasia Tchoumakova

Marketing team

Claudia Almuzara
(Marketing Director)

Tania Jassal

Jasmine Ng

Our Team

The Founders



Elena Rubini
Writing Director



Milan Singh
Graphic Editorial Director



Sofia Schönbauer
Writing Director

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REMDESIVIR'S FORESHADOWING HISTORY ON ITS FAILURE TO INHIBIT SARS-COV-2

Author: Xiaojian Qu

The world has suffered from Covid-19 for over two years, and there is no indication of when the ordeal will end. As of January 9th 2022, over 304 million confirmed cases and over 5.4 million deaths have been reported globally, and the specific medicines that are supposed to save them are still missing. During the bizarre time after the outbreak, many drugs were proven to be effective at suppressing the virus, but were proved to be of limited clinical benefit after lifting the share prices of their manufacturers. Amongst them was Remdesivir, which was held up as the people's last hope in the darkest hour of the pandemic. The final report from the New England Journal of Medicine stated that Remdesivir was superior to the placebo in shortening the time to recovery in adults who were hospitalised with Covid-19 and had

evidence of lower respiratory tract infection. Specifically, patients receiving Remdesivir had a shorter time to recover (9 to 11 days, in the 95% confidence interval, versus 13 to 18 days with the normal standard of care). Unfortunately, shortening a patient's hospital stay by just a few days is hardly the performance of a miracle drug, and its clinical performance on moderate-to-severe patients was even worse. Finally, in February 2021, the Interim WHO Solidarity Trial Results indicated that Remdesivir had little or no effect on hospitalised patients with Covid-19, as characterised by overall mortality, initiation of ventilation and duration of hospital stay. This debacle of Remdesivir's mythical effectiveness could be predicted before the drug was seen as a broad-spectrum antiviral, even before the outbreak of SARS-CoV-2.



Before talking anything further about Remdesivir, I would like to introduce Sofosbuvir, a compound used to successfully treat Hepatitis C. Its reward inspired Gilead Sciences Inc. to continue to invest in the search for a broad-spectrum antiviral which is the origin of the Remdesivir project. Hepatitis C is an infectious disease caused by the Hepatitis C virus (HCV), a positive-sense single-stranded RNA virus of the family Flaviviridae that primarily affects the liver and causes liver cancer. Sofosbuvir (Figure 1a) is a prodrug of the nucleoside analogue. Looking at the structure, its five-carbon sugar and the analogous bases (structurally similar to naturally occurring nucleobases) make a nucleoside analogue. The rest of the structure (the left side of sugar) is the working part for the prodrug and is metabolised in cells to yield the active nucleoside triphosphate (NTP/nucleotide) analogue after administration.

This nucleotide analogue could inhibit the RNA-dependent RNA polymerase (RdRp) of HCV because RdRp recognises it as a standard nucleotide and uses it to form the replicated RNA chain, hence blocking the action of RdRp. The prodrug design of Sofosbuvir was based on phosphoramidate, which was successfully targeted to enzymes in the liver. After administration, the enzymes in liver cells would firstly metabolise the prodrug into the nucleoside monophosphate analogue, which is then phosphorylated into the active nucleoside triphosphate analogue. This entire mechanism works perfectly so that Sofosbuvir is a successful specific medicine for HCV.

As I mentioned previously, the vast success of Sofosbuvir encouraged Gilead to find a compound to treat Ebola.

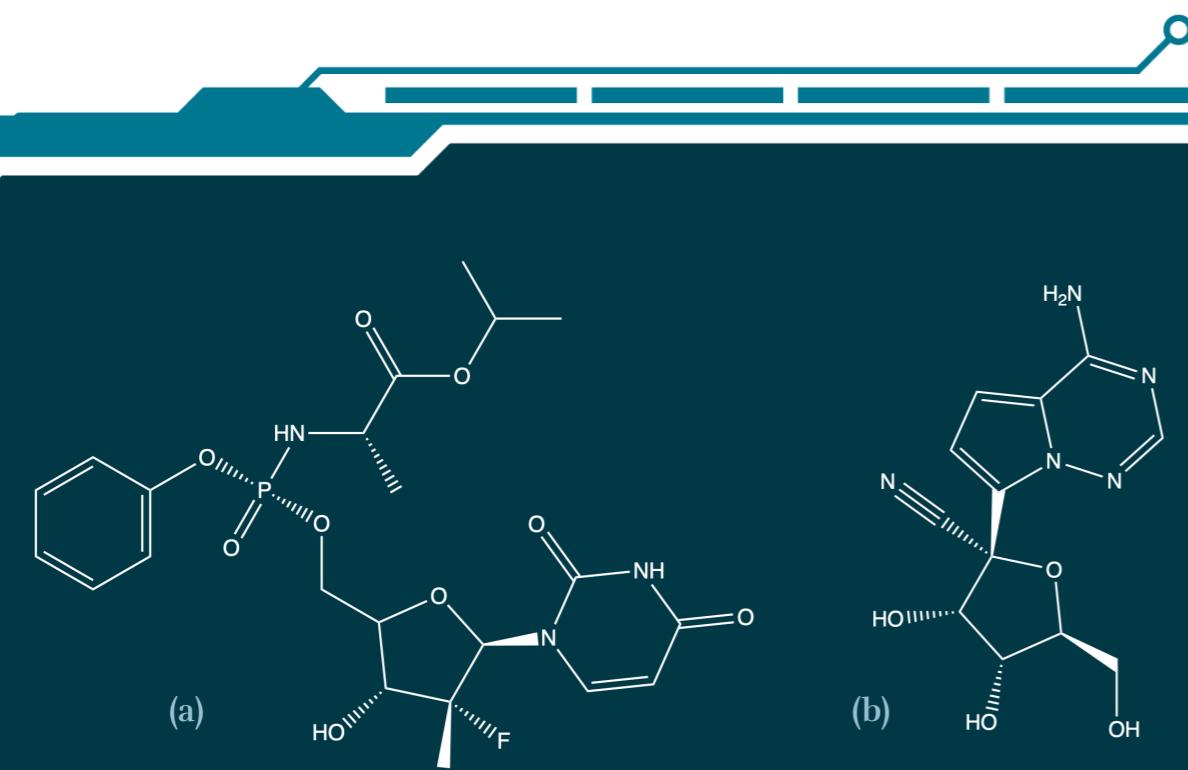


Figure 1. Structures of Sofosbuvir (a) and GS-441524 (b)

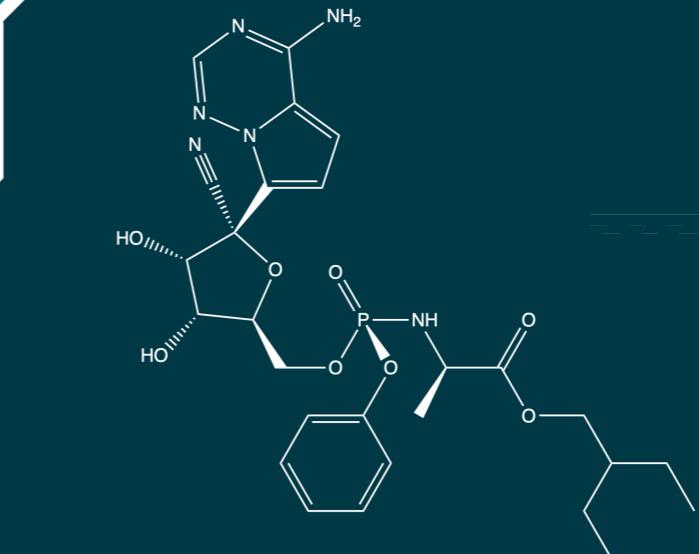


Figure 2. Structures of Remdesivir

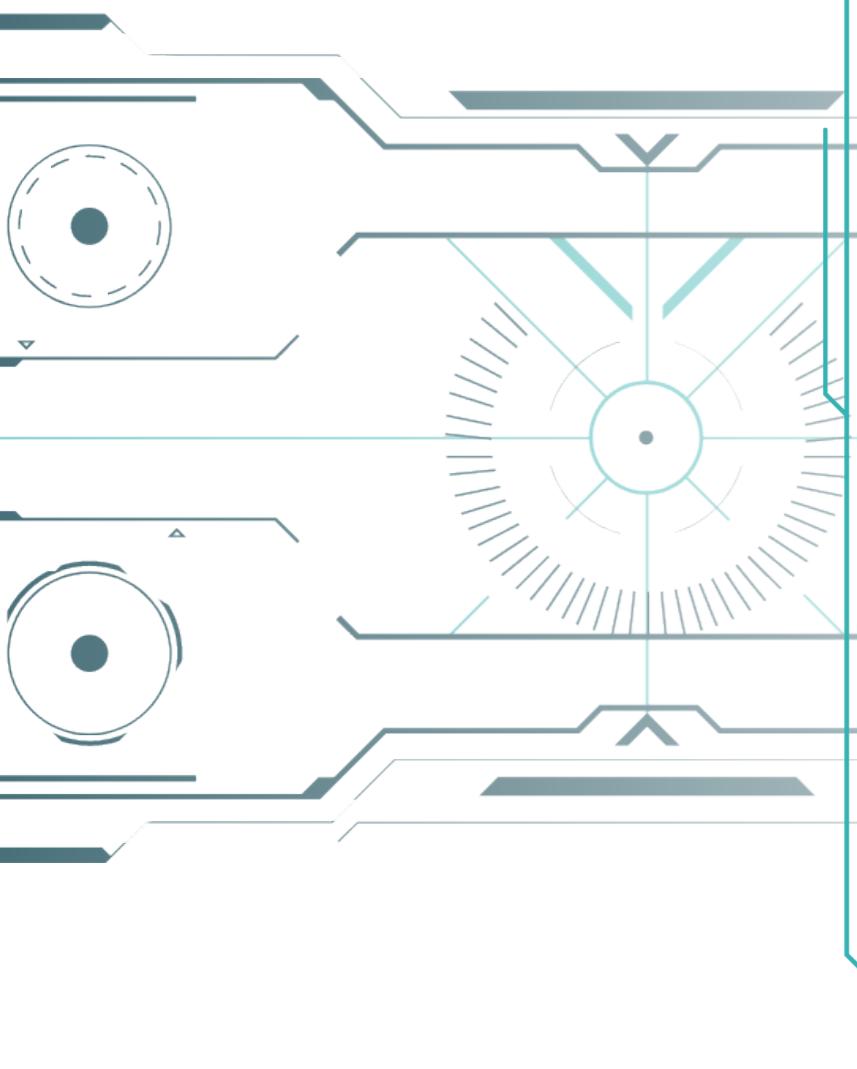
In collaboration with the Center for Disease Control and Prevention (CDC) and the United States Army Medical Research Institute of Infectious Diseases (USAMRIID), GS-441524 (Figure 1), was identified as an antiviral molecule via screening a library of nearly 1000 diverse nucleoside and nucleoside phosphonate analogues. However, the hydroxyl groups of GS-441524 are very polar, which lead to low membrane protein penetration. Thus, phosphorylation is also prolonged after GS-441524 is released in the cell, which reduces its effectiveness. As a result, a similar strategy as Sofosbuvir was applied to GS-441524, and it was then combined with the extra structure to form a prodrug. By the way, the GS-441524 itself was found to be effective against feline coronavirus strains responsible for feline infectious peritonitis (FIP), a lethal systemic disease affecting domestic cats. FIP is caused by feline coronavirus (FCoV), a positive-stranded RNA virus similar to SARS-CoV-2. This progress explains why people are confident about its broad-spectrum anti-coronavirus effectiveness.

Remdesivir (Figure 2) was then developed as the GS-441524 with the same prodrug structure as Sofosbuvir. YES! **THE SAME PRODRUG STRUCTURE!** As a result, Remdesivir inherited Sofosbuvir's liver targeting function. Unfortunately, its oral hepatic first-pass metabolism is too strong, so it is almost impossible to develop further as an oral drug. However, as the target disease was Ebola, this was deemed acceptable for further research as the rapid progress of the Ebola virus damages the gastrointestinal tract, so the oral administration is insignificant and intravenous administration is more effective. However, Remdesivir was proved less effective than monoclonal antibodies in the treatment of Ebola, so the whole program was shut down until the outbreak of SARS-CoV-2.

Both GS-441524 and Remdesivir are proven to be effective in inhibiting SARS-CoV-2 in vitro and in rhesus monkeys, which brought hope and boosted Gilead's stock price in the early days of the pandemic.

However, it eventually failed to cure Covid-19, which is understandable due to its history. After intravenous injection, Remdesivir is converted into its parent nucleoside GS-441524 in plasma, which may enter cells slowly, and is converted into monophosphate even more slowly after entering cells. The phosphoramidate prodrug design leads to liver targeting, and it could be metabolised well in hepatocytes, peripheral blood monocytes, macrophages etc. Unfortunately, all those cells are not the target of SARS-CoV-2 since it primarily acts on cells associated with the respiratory tract!

Furthermore, Remdesivir can't kill the virus, and it can't repair the organ damage caused by the virus; the only thing it can do is stop viral replication.



Thus, Remdesivir needs to be administered at the very early stage of infection, even before the infected people show relevant symptoms. Due to its previous design for Ebola, it can only be administered by intravenous injection, which must be carried out by a medical professional in a medical institution. As a result, Remdesivir has anti-SARS-CoV-2 activity, but it is not effective in many day-to-day situations. Gilead definitely had the ability and the opportunity to modify GS-441524 to a more suitable structure. Yet, they chose to roll out the old product as soon as possible, plausibly for the rise in stock prices observed.

Have you heard of our ongoing collaboration with the *Chemistry Seminar Series* at Kin'gs College London?

Organised by Dr Reading, Dr McTernan and Dr Muller, the university hosts a broad range of chemistry talks twice a month.

Head over to our Astrochemistry edition (page 15) featuring a cutting-edge interview with Dr Dodani!

Talk with Experts

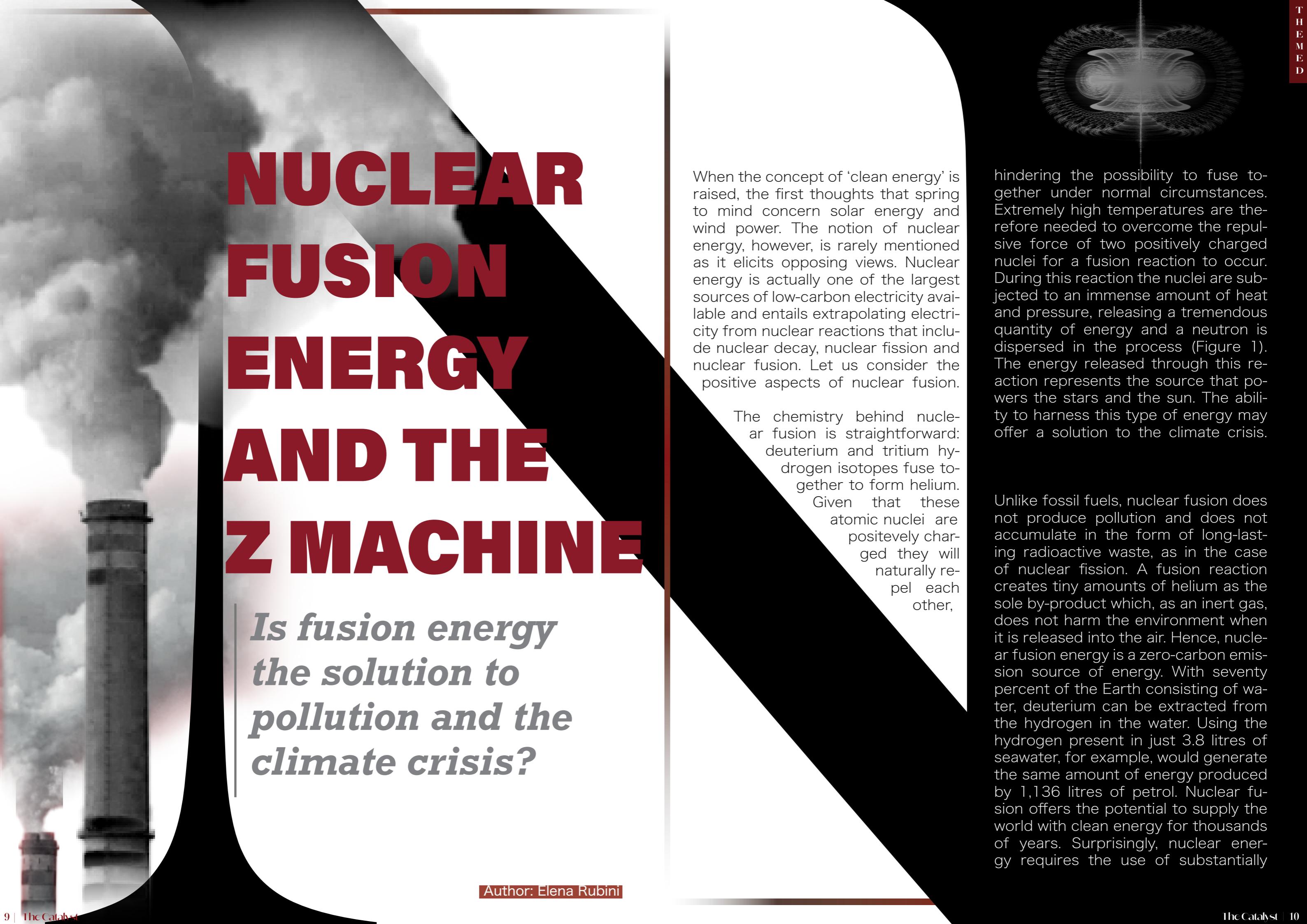
Dr. Sheel Dodani
Assistant Professor at
The University of Texas at Dallas

We've all once added NaCl (table salt) to our food to make it taste better, but did you know that there are approximately 115 g of chloride (Cl^-) in your body? Biological receptors that selectively detect and position sodium (chloride's cationic counterpart) have been extensively studied in cell biology. However, anions such as Cl^- are scarcely understood, despite also serving as essential nutrients for life. Dr. Dodani's interest lies in understanding "the who, what, when, where, and why of what anions are doing in living cells." This has wide therapeutic implications because dysregulation of anions implicated in a plethora of diseases from cystic fibrosis to neurological disorders. To address this and "accelerate biological insights with molecular technologies", the work of Dr. Sheel Dodani is crucial.

Interview WITH DR SHEEL DODANI

The Catalyst, in association with the KCL Chemistry Department Seminar Series 2021/2 is delighted to present the first of an ongoing series of Talks with Experts. In this series we sit down with researchers working on the front lines of scientific advancement to delve deeper into their cutting-edge research and gain insight into how they have successfully attained the distinguished positions they hold today. Now, grab a chair and join us on a journey through today's technology and incredible research.

Dr. Dodani is an Assistant Professor at The University of Texas at Dallas (UT Dallas), where in addition to teaching various (bio)chemistry courses, she leads the Dodani Lab. Her highly skilled research team is focused on building a chemical biology toolkit, based on engineering turn-on, fluorescent protein-based biosensors for halides (specifically chloride) and oxy-anions. These imaging tools would provide spatial and temporal resolution to help us understand the exact role, location, and mechanisms of anions within our body. On a fundamental level, her research aims to shed light on the thermodynamics and kinetics of anion-protein interactions. Crucial work which Dr. Dodani enjoys because "[...] you never know what you will learn. We do not talk about anions



NUCLEAR FUSION ENERGY AND THE Z MACHINE

*Is fusion energy
the solution to
pollution and the
climate crisis?*

Author: Elena Rubini

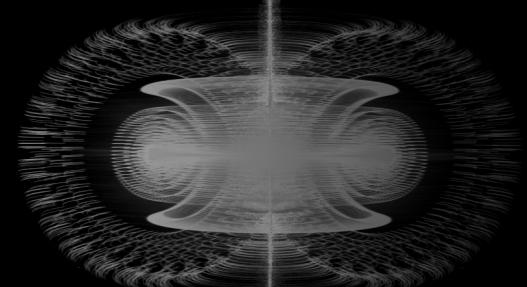
When the concept of 'clean energy' is raised, the first thoughts that spring to mind concern solar energy and wind power. The notion of nuclear energy, however, is rarely mentioned as it elicits opposing views. Nuclear energy is actually one of the largest sources of low-carbon electricity available and entails extrapolating electricity from nuclear reactions that include nuclear decay, nuclear fission and nuclear fusion. Let us consider the positive aspects of nuclear fusion.

The chemistry behind nuclear fusion is straightforward: deuterium and tritium hydrogen isotopes fuse together to form helium.

Given that these atomic nuclei are positively charged they will naturally repel each other,

hindering the possibility to fuse together under normal circumstances. Extremely high temperatures are therefore needed to overcome the repulsive force of two positively charged nuclei for a fusion reaction to occur. During this reaction the nuclei are subjected to an immense amount of heat and pressure, releasing a tremendous quantity of energy and a neutron is dispersed in the process (Figure 1). The energy released through this reaction represents the source that powers the stars and the sun. The ability to harness this type of energy may offer a solution to the climate crisis.

Unlike fossil fuels, nuclear fusion does not produce pollution and does not accumulate in the form of long-lasting radioactive waste, as in the case of nuclear fission. A fusion reaction creates tiny amounts of helium as the sole by-product which, as an inert gas, does not harm the environment when it is released into the air. Hence, nuclear fusion energy is a zero-carbon emission source of energy. With seventy percent of the Earth consisting of water, deuterium can be extracted from the hydrogen in the water. Using the hydrogen present in just 3.8 litres of seawater, for example, would generate the same amount of energy produced by 1,136 litres of petrol. Nuclear fusion offers the potential to supply the world with clean energy for thousands of years. Surprisingly, nuclear energy requires the use of substantially



Deuterium

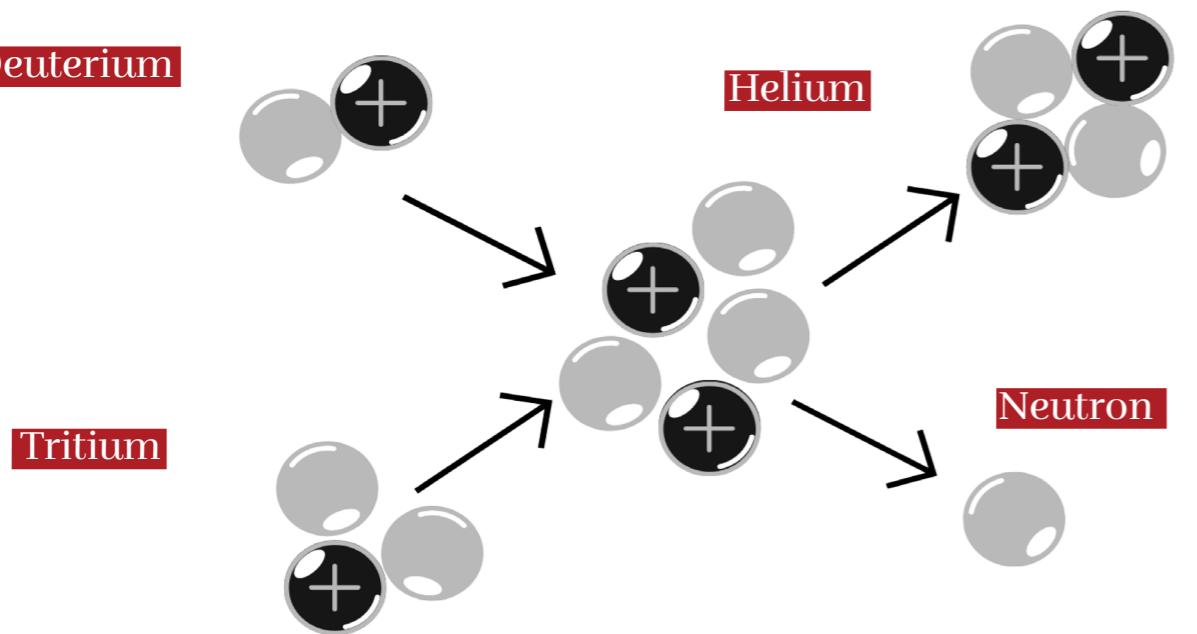


Figure 1. Nuclear fusion of tritium and deuterium.

less surface area to produce electricity compared to any other renewable energy source. For instance, the amount of energy generated from a nuclear reactor is equivalent to over 3 million solar panels, or 440 wind turbines, that necessitate an extensive amount of land to house the solar panels and wind turbines. From a macro perspective, some 52 billion solar panels are necessary to power the entire world, equivalent to the entire surface area of the United States of America. Fourteen thousand nuclear power plants, on the other hand, are sufficient to meet the world's energy needs.

Nuclear energy represents an incredibly efficient source of energy. Nuclear fuel is extremely dense and a single nuclear pellet, the size of a tic-tac mint, is equivalent to one tonne of coal. Nuclear energy is a valid alternative to fossil fuels: one kilogram of fusion fuel is capable of providing energy equivalent to 10 million kilograms of fossil fuel. Additionally, nuclear fusion is considered safer than nuclear fission reactions because it does not rely on chain reactions which can lead to a nuclear meltdown.

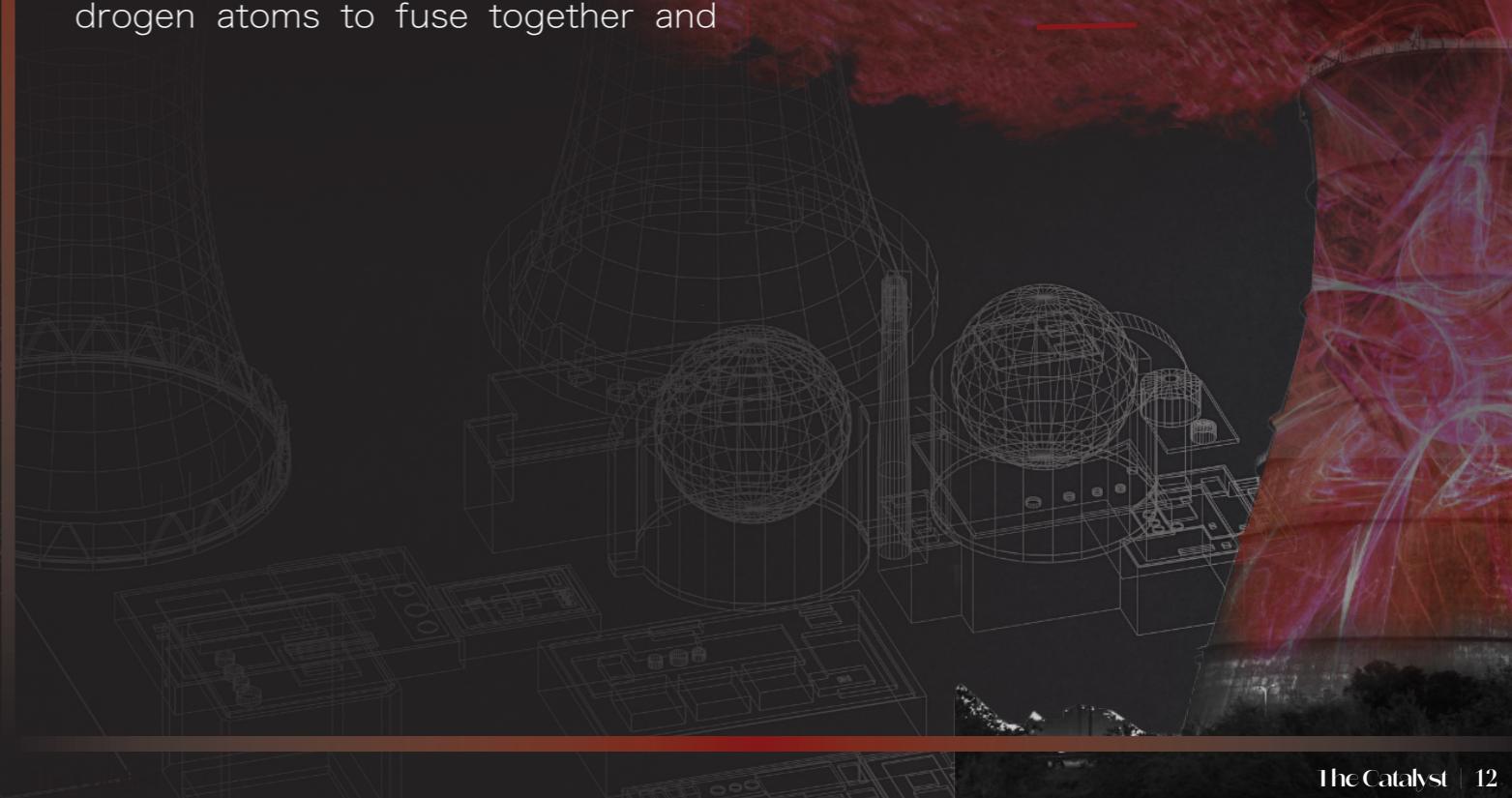
If a problem is encountered within a reactor, the fusion reaction will cease without leading to a runaway reaction that causes severe damages.

If nuclear fusion energy is so advantageous and efficient, why haven't we taken advantage of this source and solved all of the world's energy and climate issues? The answer is quite simple: reaching extraordinarily high temperatures of over 100 million degrees is extremely difficult. We know that fusion reactions occur within stars and at the centre of the sun. Therefore this means that we need to simulate temperatures as hot as the sun itself. Many scientists continue to be sceptical about this challenge, however, we may be closer to creating fusion energy today than we envisage. A nuclear reactor called "Z machine" resides in Albuquerque, New Mexico. It was built by the Sandia Labs and is used to further our knowledge of many fields such as fusion energy, nuclear weapon control and X-ray research. The Z machine is a fusion reactor that is essentially a giant battery. It is charged to 82 thousand volts and when the green button labelled 'Fire' is pressed,

it emits a shock of 20 million amperes. The emission of the initial electrical pulse goes through a series of stages where it is compressed in space to generate the most extreme pulse of electrical power on earth.

produce copious amounts of energy. Fundamentally, the scientists at this facility have 'created' what many are calling 'a star on Earth'.

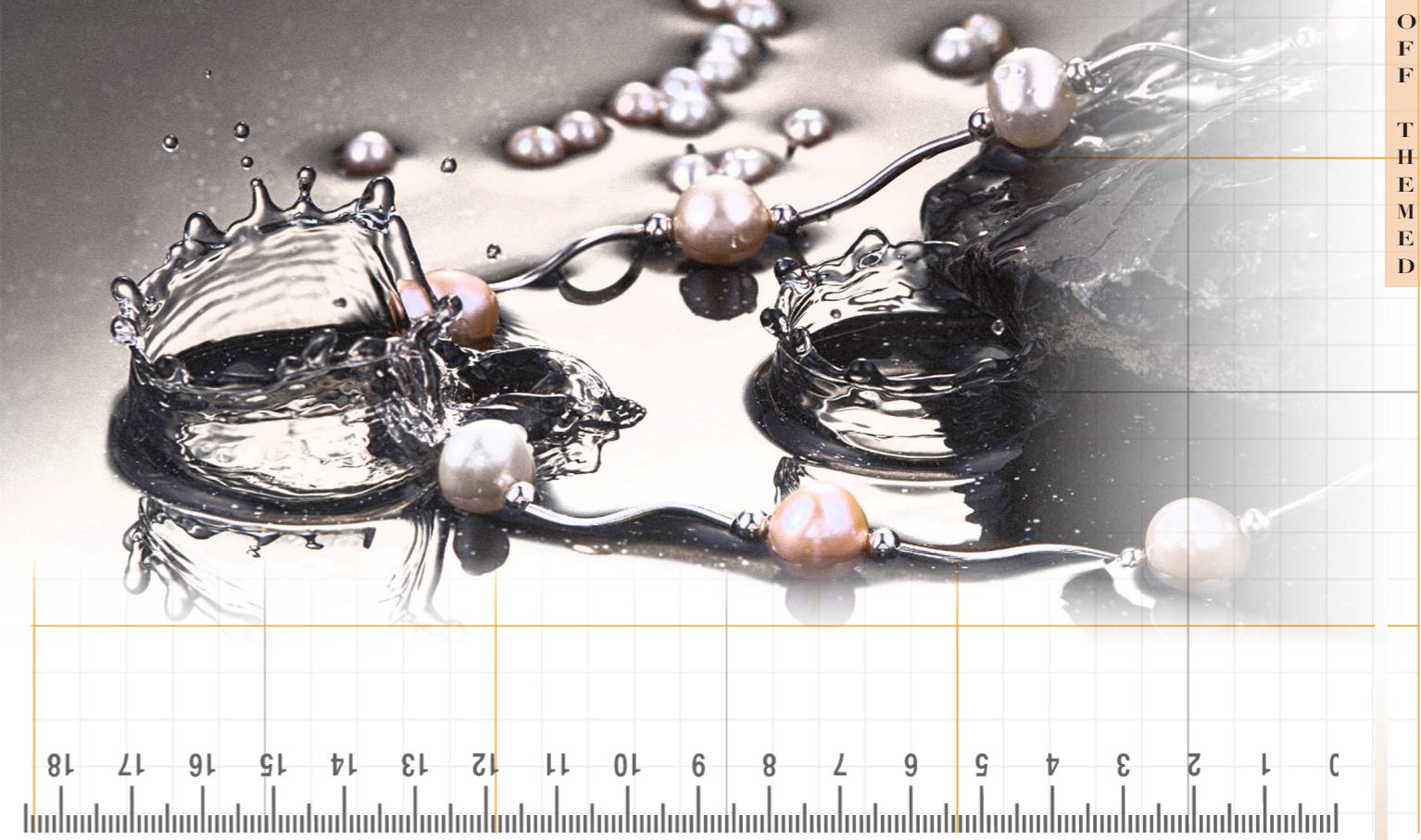
This innovative and unique tool is the stepping stone towards truly understanding how to control and use nuclear fusion energy to power our planet for millions of years using clean energy. The scientists who work at this facility are learning more about this complex science every day in order for us to someday benefit from this powerful energy. But before we arrive at a solution for the pollution and climate crisis, many scientific fundamentals have yet to be established. The science in this field continues to develop and the Sandia Labs collaborates with prominent universities to further this fundamental research on physics and astrophysics. Will nuclear fusion energy represent the solution to the energy crisis that we have been waiting for? Will the Z machine be the vehicle that transports us to our much desired destination? The answers to these questions are not yet defined but are fast-approaching.



THE NANOSCALE PRECISION OF



Author: Louis Weiss



Despite a century of scientific fascination regarding the symmetry of nature, there remains a fundamental question of whether long-range order exists, where atomic particles show periodicity over a large range of their diameters. Today, despite modern technological advancements, the perfect sphere remains a theoretical concept, because the idea of a smooth surface fails at an atomic level. However, research that could inform future high-performance nanomaterials has been conducted. A University of Michigan-led team in 2021 uncovered for the first time how molluscs build ultra-durable structures with a level of symmetry that outstrips everything else in the natural world, with the exception of individual atoms. Making something with nanoscale architecture as intricate as a pearl remains out of reach, however a lot can be learnt from pearls. They are capable of transforming a disordered nothingness into a structure with the highest level of symmetry and order in the organic world.

All shelled molluscs, by natural processes, can produce pearls of some kind. However, only a small minority are considered gemstones. The best known and commercialised pearls - nacreous pearls - are primarily produced by 2 types of molluscs: bivalves or clams. Nacreous pearls are made from layers of nacre, a strong inorganic composite that also forms the inner shell lining in these molluscs. This is composed of calcium carbonate minerals in minute crystalline form, such as aragonite and calcite.

The formation of a natural pearl is believed to begin with a microscopic intruder entering and settling in a clam or bivalve. This irritates the mollusc, which begins to form a pearl sac of external tissue cells around the impurity or parasite.



This sac is then covered by secretions of calcium carbonate and complex proteins known as conchiolins. Then, layers of nacre, the iridescent and extremely durable organic-inorganic composite that also makes up the shells of oysters and other molluscs, build on this organic centre. They make up more than 90% of a pearl's volume, become progressively thinner and more closely matched as they build outward from the centre, forming near spherical structures.

A study published in the Proceedings of the National Academy of Sciences found that a pearl's symmetry becomes increasingly precise as it grows, answering centuries-old questions about how the disorder at its centre becomes a structure of architectural perfection. Perhaps the most surprising finding is that molluscs maintain the symmetry of their pearls by adjusting the thickness of each layer of nacre. If one layer is thicker, the next tends to be thinner, and vice versa. The study observed 2,615 finely matched layers of nacre, deposited over 548 days.

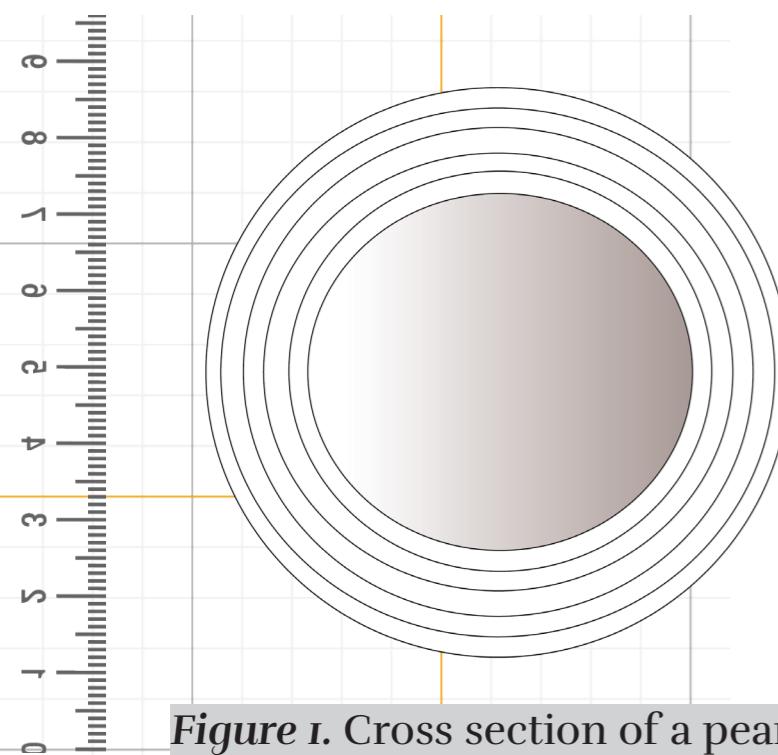


Figure 1. Cross section of a pearl.

The team gathered their observations by studying Akoya "keshi" pearls, produced by the Pinctada imbricata fucata oyster in Eastern Australia. They selected these particular pearls, which measure around 50 millimetres in diameter, because they form naturally, as opposed to bead-cultured pearls which have an artificial centre. Each pearl was cut with a diamond wire saw into sections measuring three to five millimetres in diameter, then polished and examined under an electron microscope.

Robert Hovden, UoM Assistant Professor of Materials Science and Engineering and an author on the aforementioned paper, likened the thin, smooth layers of nacre to bed sheets, with organic matter in between them:

"there's interaction between each layer, and we hypothesise that that interaction is what enables the system to correct as it goes along."



A mathematical analysis of the pearl's layers show that they follow a phenomenon known as '1/f noise' where a series of events that appear to be random are connected, with each new event influenced by the one prior. 1/f noise has been shown to govern a wide variety of natural and synthetic processes including seismic activity, economic markets, electricity, physics, and even classical music. When a die is rolled, every roll is mutually exclusive and independent from the previous. On the contrary, in regard to 1/f noise, each event is linked. With each addition of a nacre layer there is a structure and complex mechanism that cannot be predicted; that coalesces over thousands of layers, towards order and precision. The study also found that pearls lack true long-range order, often observed in architecture such as skyscrapers, which maintain consistency in the symmetry of hundreds of layers of bricks. Pearls exhibit intermediate-range order, so the symmetry is maintained approximately 20 layers at a time. However, this is enough to maintain the high degree of symmetry and durability over the thousands of nacre layers over time. Fundamentally, there is a trade off between achieving the greatest symmetry with the

addition of each layer and minimising variation in layer thickness. The result is remarkable periodic ordering.

Another 2021 study, published by the Technische Universität Dresden, showed some similarities, with research specifically concerning how the structural defects in mother-of-pearl attract and cancel each other out, permitting the assembly of perfect architecture. They found that defects of opposite directions were attracted to each other from great distances; the right- and left-handed defects shifted through the structure until they met, resulting in mutual annihilation. This led to a tissue-wide synchronisation which gave rise to the mother-of-pearl's regular and flawless architecture.

Hovden says the study's findings could help inform the next generation of materials with precisely layered nanoscale architecture. Brick buildings take time, careful planning, measuring and templating. These molluscs can achieve similar results on the nanoscale using a different strategy. Perhaps a lot is to be learnt from them, to make stronger and lighter materials in the future.

The Chemistry Behind RADIOTHERAPY

Ever since the discovery of X-rays in 1896 by German physicist Prof. William Conrad Röntgen, radiation therapy has been an essential part of the diagnosis and treatment of a multitude of diseases, despite the potential hazardous effects radiation can have. So, how have we been able to utilise radiotherapy in the treatment of cancer?

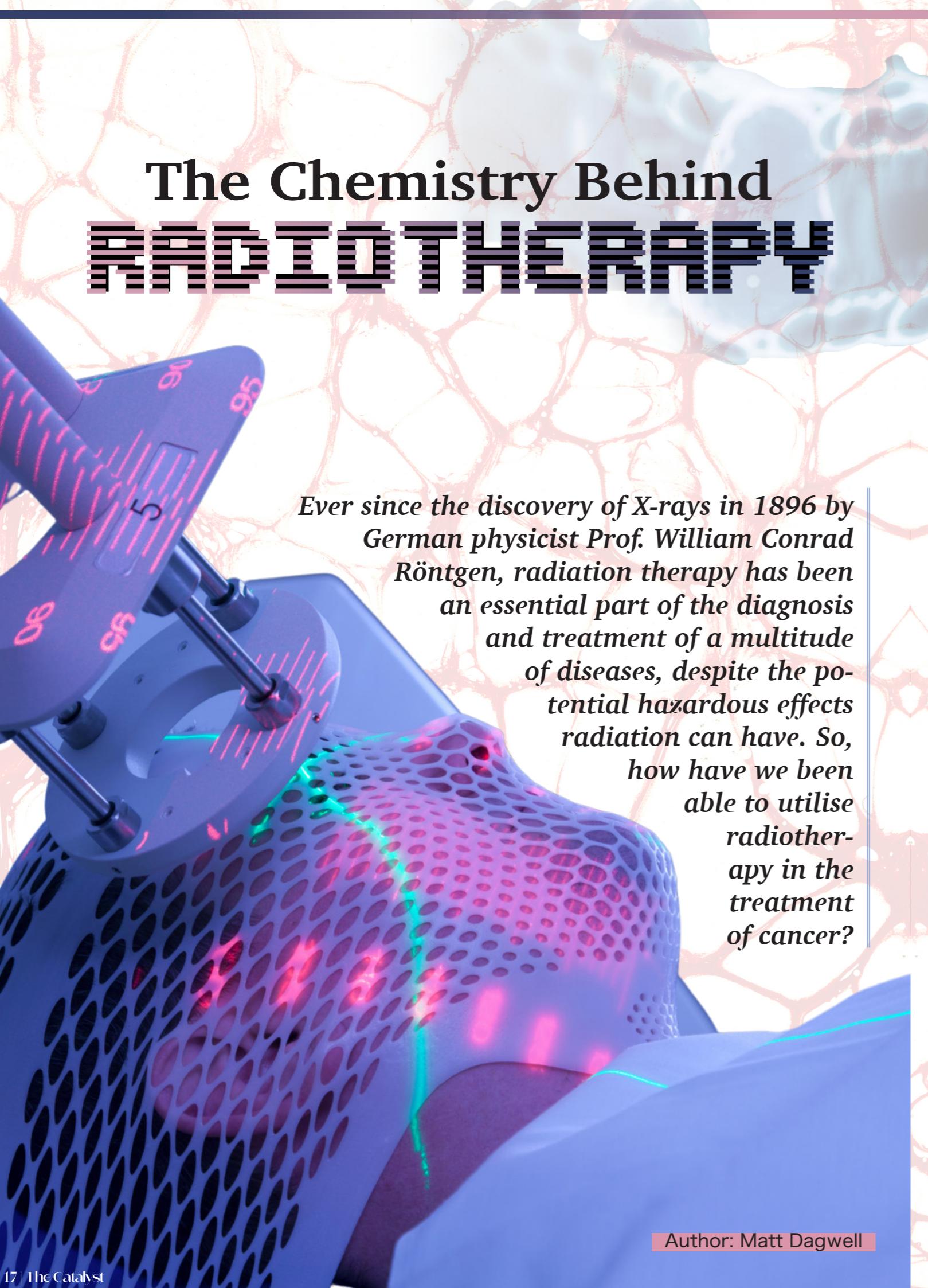
Author: Matt Dagwell

To understand how radiotherapy works, an understanding of the cell cycle and how cancer forms is imperative. During the cell cycle (the replication of cells), there are 5 phase processes that are controlled by specific proteins known as cyclin-dependent kinases (CDKs). The cell first starts at rest (G₀ phase), where it is in a completely undivided state. This is then followed by the cell increasing in size, with duplication of the cell's most important components including key proteins (G₁ phase), DNA and chromosomes (S phase). Following this, the cell continues to grow and prepares for separation (G₂ phase), finally climaxing at the M phase, where full mitosis of the cell occurs along with cytokinesis, eventually forming two daughter cells.

So, what goes wrong in cancer? In cancer, the cell cycle process is non-stop even after a successful division has occurred. The cells continue to divide due to cancerous mutations in the DNA essentially bypassing the key

"DNA checkpoints" that ensure it isn't damaged in any way that could harm the cell. This process is especially prominent in cells that have high replication rates, such as the lungs, liver and brain.

To combat these diseases with non-chemical methods, clinicians will often use radiotherapy in the form of two main types of radiation: photon radiation and particle radiation. Photon radiation utilises a high energy beam of radiation, usually X- or gamma rays produced by radioactive isotopes of cobalt or caesium, or alternatively a machine called a linear accelerator. Radioactive isotopes such as cobalt-60 and caesium-137 are able to emit both beta and gamma radiation as they decay, which then pass through the body and are directed at cancerous cells, causing a breakdown of DNA and thus cellular death. This consequently kills cancer cells and decreases the amount of cancer within the body.



Particle radiation describes the use of different particles to target cancer cells. There are several different types of particle radiation, the first being the **electron beam**. This beam is produced by a linear accelerator and does not penetrate the body as deeply due to its fairly low energy level. Consequently, this type of radiation is used to treat cancers of the skin, as well as tumours and lymph nodes that are close to the surface of the skin. The second type of particle radiation is the **proton beam**. This beam utilises a key property of the proton: the delayed release of energy. This delay in energy release means that the proton doesn't cause damage to the healthy tissues surrounding the cancer, before it reaches its target. However, as brilliant as this treatment is, it is not very widely available.

Three additional types of particle beam are also utilised in particle radiation therapy, including neutron beams, carbon ions and alpha/beta particles. The **neutron beam** uses its neutral charge to treat - most commonly - cancers of the head, neck and prostate. The patient is first injected with a non-radioactive isotope of boron-10 which acts as a neutron trap in the cancerous cells due to its high propensity to capture low energy neutrons. The patient is then irradiated with epithermal neutrons (neutrons of energy greater than thermal energy (0.025eV). These epithermal neutrons then enter the body and combine with boron-10 in the cancerous tissue, with this fission reaction then leading to the emission of alpha particles that are able to kill the cancer cells.

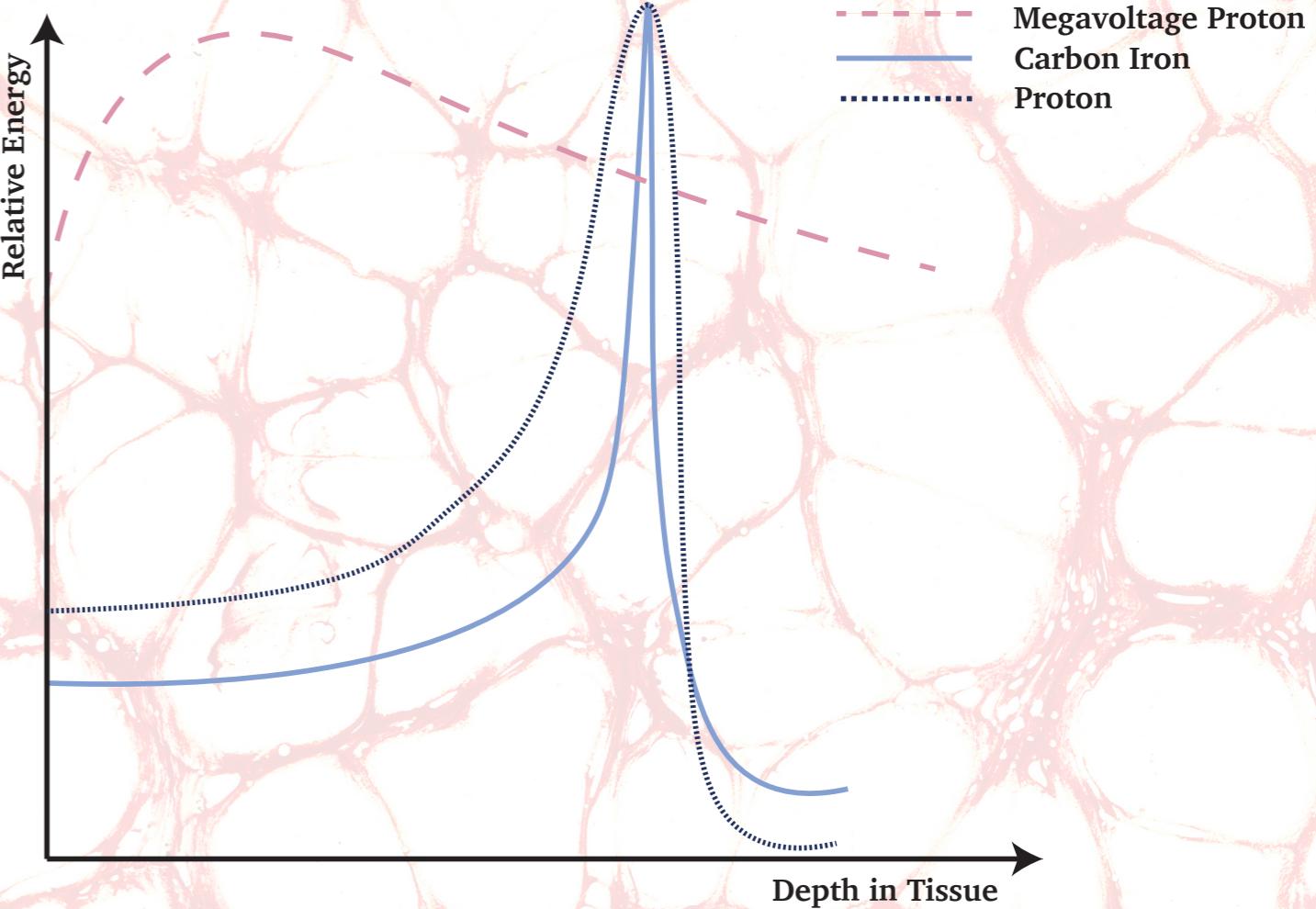


Figure 1. Graphs of dose deposition at depth 6 MV photons, protons and carbon ions.

Carbon ion therapy is an innovative method of radiotherapy that was developed in order to treat radioreistant cancers. Carbon ion theory is useful in its energy release timings, similar to proton therapy. Carbon ions exhibit a characteristic energy distribution known as the **"Bragg peak"** where low levels of energy reach the tissues surrounding the cancerous cells, but high energy levels are deposited in the target tissue, consequently making them advantageous when treating specific cancers such as meningioma and high-grade glioma.

Overall, the understanding of radioactivity has proven to be arguably one of the most important discoveries of the 19th and 20th centuries, having a multitude of effects across the medical field from imaging to therapy. Hopefully, this will continue to grow as an area of both physics and chemistry to aid in the overall improvement of human health.

A sensory exploration into the world of molecular Gastronomy

Author: Elena Rubini

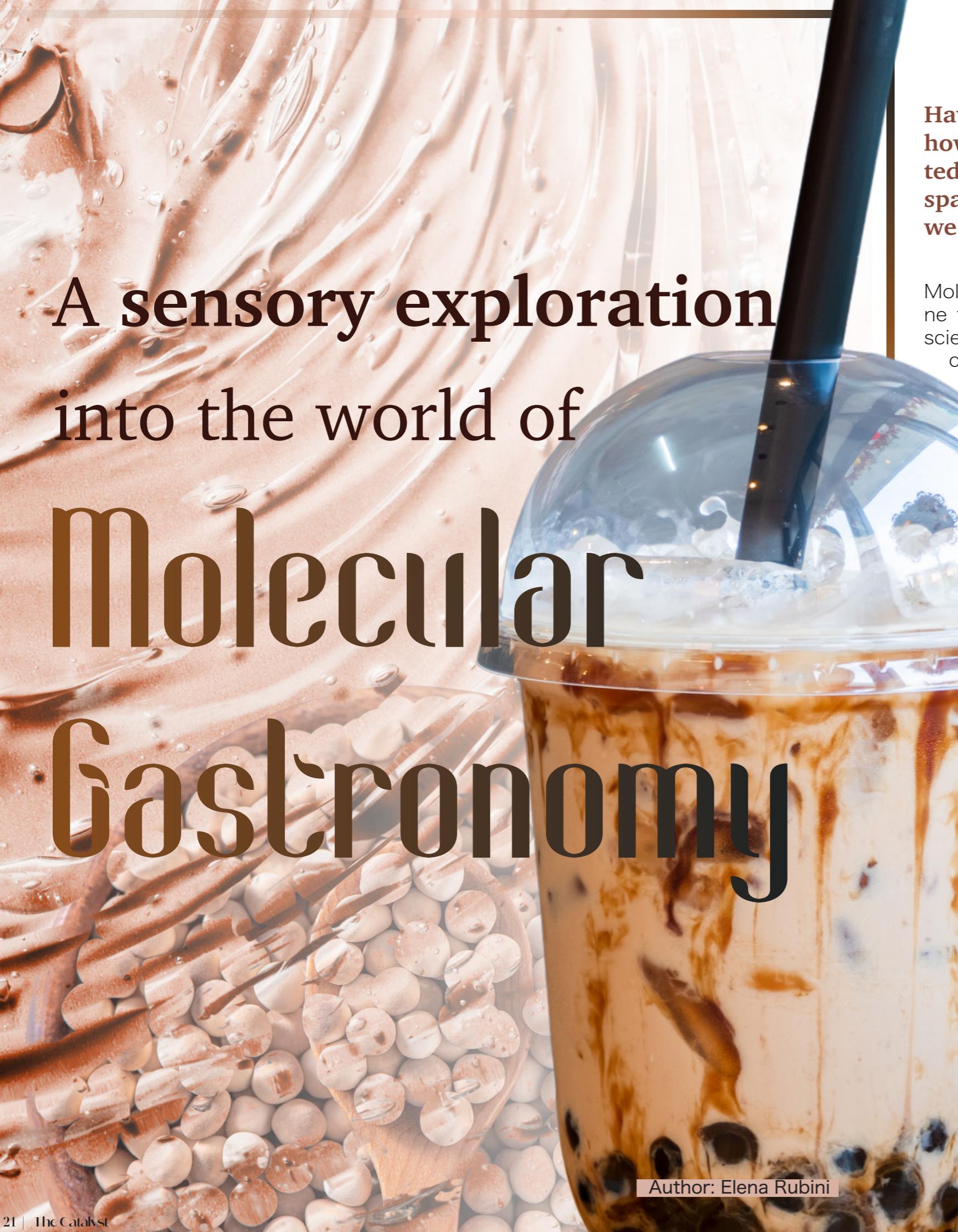
Have you ever found yourself sipping on a bubble tea and wondered how the phenomenon of ‘bubbles’ bursting in your mouth is created? Have you experienced eating a culinary creation that tastes like spaghetti and meatballs but has no resemblance to the popular dish we all love? Welcome to the world of molecular gastronomy.

Molecular gastronomy is the discipline that brings together cooking and science by seeking to understand the chemical and physical transformations that take place during cooking while exploring new culinary possibilities. Innovative and creative new techniques are used to make food that tastes delicious but also presents an artistic ‘wow’ factor, changing the way that chefs approach cooking today.

Molecular gastronomy refers to the use of ingredients combined in a **colloidal system**: a mixture of substances whereby one part is dispersed throughout another but they do not combine to form a solution. Ingredients employed in a colloidal system undergo chemical and physical modifications and chefs purposefully use techniques such as spherification, gelification and liquid nitrogen as a freezing agent to achieve these transformations.

Let us examine some of these modern cuisine techniques and the chemistry involved. **Spherification** is the process that leads to the controlled gelification of a liquid, thereby transforming it into a sphere with a thin gel membrane. A chemical reaction occurs when sodium alginate comes into contact with calcium chloride. Sodium alginate is a compound formed from negatively charged alginic acid (extracted from seaweed) and positively charged sodium ions that bind to the alginic acid molecules. Once dissolved, the sodium ions dissociate from the alginic acid molecules forming a liquid solution. When sodium alginate is added to a calcium chloride solution, the alginic acid molecules bind to the calcium ions to create calcium alginate. As calcium ions are doubly charged, they can bind to different alginic acid molecules simultaneously, leading the solution to thicken and take the shape of a gelatinous substance.

Modern chefs often use this procedure to create components such as spherical mango “ravioli” or caviar-like peas. The purpose of spherification is to create a **textural sensation** in the palate as a spherical ingredient will hold its shape until bitten when an explosion of flavour is released. This technique of spherification was pioneered by the acclaimed three Michelin star chef Ferran Adrià and his team at his famous El Bulli restaurant in Spain.



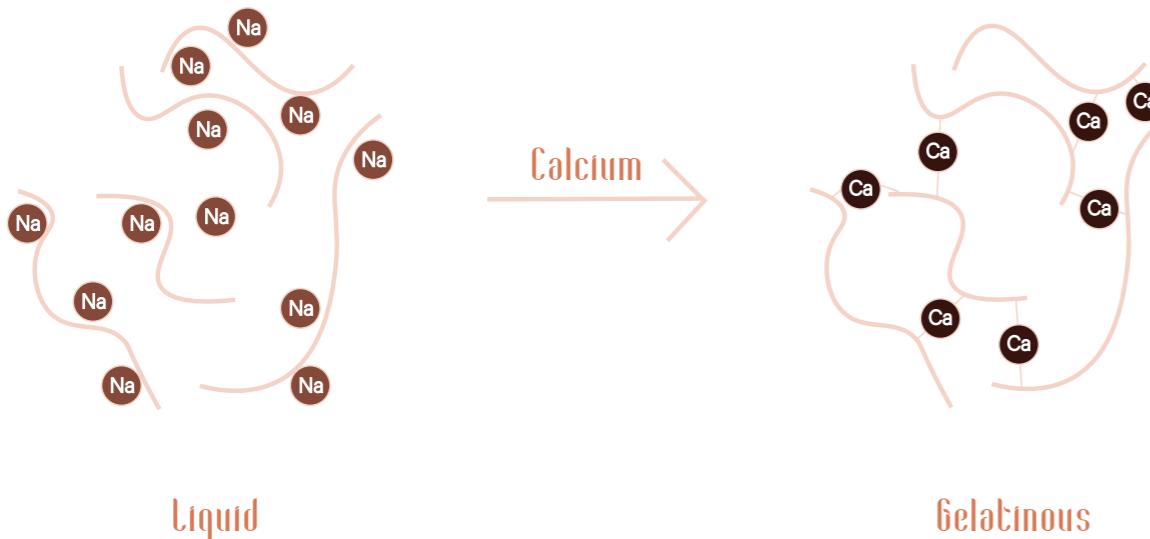


Figure 1. Diagram of Gelification

In culinary practice, spherification is achieved by evenly dispersing sodium alginate into a flavoured liquid (typically using a ratio of 0.5g of sodium alginate to every 100g of liquid) and plunging the solution into a bath of cold water mixed with calcium chloride (applying the same proportions of 0.5g to 100g of water). Upon contact with water, the liquid disperses and each droplet begins to encapsulate into a bubble. Once the spheres are formed, they can be transferred into another bath of fresh water to wash off the solution and are ready for serving.

Gelification, a technique similar to spherification, implies forming a gel. Molecular gastronomists like to use this technique to make interesting flavoured spaghetti or pearls, for instance. Various types of additives commonly employed in cooking, such as gelatin, agar and iota carrageenan, are used to create different gels. The gels assume a semi-solid form when they are made as the molecules are arranged to form a spider web network, trapping the softer part in the centre and having a more robust characteristic on the surface.

The molecules are not held together through covalent bonds, but through weaker intermolecular forces such as hydrogen bonds, Van der Waals and electrostatic forces. The spider web network of molecules prevents compounds contained in the soft centre from aggregating and thereby allows preservation of the semi-solid state. Depending on the type and concentration of the gelling agent, the results can be quite remarkable, ranging from elastic gels using iota carrageenan to firm and brittle gels made with agar. This allows cooks to target the shape and texture to suit the desired gastronomic effect, for example **papaya gel noodles** used as a garnish or balsamic vinegar gel pearls to decorate a dessert.

Let us now consider freezing techniques using **liquid nitrogen**, a compound often used by chemists in experiments. From a culinary perspective, we may recall an experience at a restaurant in which an impressive vapour cloud “falls off” the plate served to us, leaving us in awe of the ‘wow’ effect of this phenomenon. As chemists, however, we quickly realise that the vapour

is simply hydrogen formed from the condensation of the surrounding air. Apart from creating an aura of remarkable astonishment among clientele, chefs choose to use liquid nitrogen for its extremely rapid cooling capabilities. The ability to make ice cream in just a few minutes is highly advantageous compared to using equipment like ice-cream churning and traditional freezers that may require hours. Liquid nitrogen enables the fat and water particle structure of the cream to remain intact, giving the ice cream its creamy and smooth texture. Using liquid nitrogen also avoids the formation of large water crystals commonly found in traditional freezers. The rapid freezing process associated with the use of liquid nitrogen to create certain foods also has the added advantage of preserving the nutrients. The late Chicago-based chef Homaru Cantu was known for the groundbreaking invention of the **edible menu**,

including the so called ‘bread and butter’ menu. A modified ink-jet printer is used to print the menu and the ink cartridges are filled with food-based ink, such as juice from carrots, tomatoes and beetroots. Chef Cantu has taken culinary inventions to the next level with his innovative version of classic **fried chicken** composed of noodles and southern biscuits made with dehydrated freeze-dried chicken ground into a powder. At first glance, the dish has no resemblance to fried chicken but after the first bite your palate is filled with the sensation of exquisite fried chicken.

While molecular gastronomy might appear a new trend developing in the culinary world, this field simply applies chemical and physical principles established by science.

Combining science, food and creativity, molecular gastronomy is exploiting the applications of chemistry to new frontiers, demonstrating the true versatility of this natural science. From pearl ravioli to edible menus, I am looking forward to a sensory dining experience at a restaurant run by a molecular gastronomist.





OUR NUCLEAR ENERGY PROBLEM:

how
can
we
reprocess
and
reuse
our
nuclear
waste?



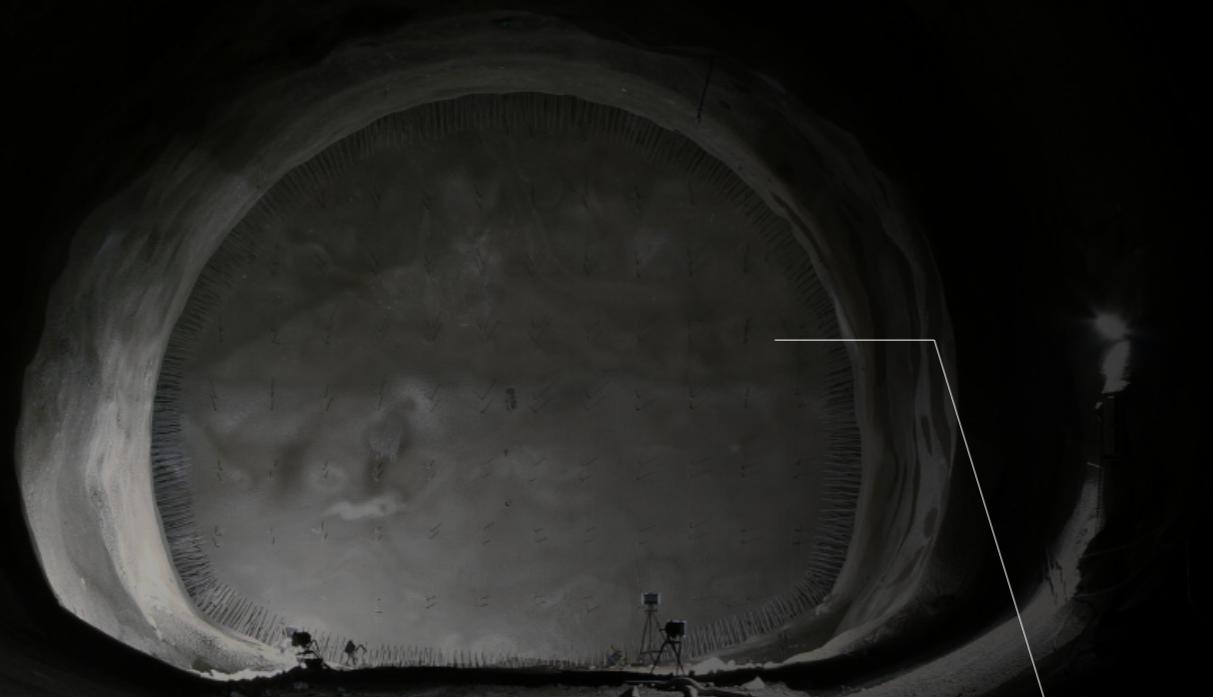
Undeniably, nuclear power produces an abundant source of energy with the potential to address energy security concerns of the entire humanity for a prolonged period of time; but serious attention is required for the eventual elimination of nuclear waste that is piling up in temporary storages.

Author: Louis Weiss

As with any energy-production pathway, the costs incurred through nuclear recycling are high, and in the past, the amount of energy needed to recycle the fuel was greater than the energy produced. However, the recycling of nuclear waste has become much more efficient, and new techniques are making it more viable all the time. The United States still refuses to recycle its high-level nuclear waste and has more than 70,000 tons of it stored at various nuclear plants around the country. America's ban on spent fuel recycling, established in 1977, is still in place and keeps the country from being a true leader in sustainable energy independence. One reason for this is the fear that terrorism and other criminal activity will result in attempts to steal recycled nuclear waste. To date, no spent nuclear fuel has been repurposed or proliferated via nuclear fuel recycling. This in-built safety is due to high levels of oversight and security, as well as the cost and technical rigour required for the process.

Other countries such as France, Japan, Belgium, Germany, Switzerland and Russia, have taken a more progressive stance, and regularly recycle their nuclear energy. While the cost and infrastructure setup for nuclear waste recycling is high, mitigating the need for long-term storage repositories and preventing the depletion of uranium resources is worth the trade-off. As the costs of nuclear waste storage continue to rise, recycling spent fuel will become a necessity for the nuclear nations of the world. Clearly, there are options for recycling nuclear waste and reducing the need for risky storage techniques,

so what is stopping countries from investing fully in this type of sustainable technology?



underground nuclear waste depository site

DANGER



radioactive sign

WHAT IS NUCLEAR WASTE?

Nuclear waste is a broad term that describes several things, including materials that have been contaminated by radiation, such as the structural material of the remaining buildings surrounding Chernobyl, or by-products of certain medical and research tasks. In medical offices and hospitals, you will often see warning signs on some disposal bins with the symbol for radioactive waste. This type of waste can usually be incinerated or compressed, and then buried. However, for the purposes of this article, we'll be discussing the most common and controversial form of nuclear waste - spent nuclear fuel - which is generated after nuclear fuel is used in a reactor for energy generation, or by other nuclear technologies!

A common misconception about nuclear waste is its depiction as a glowing, green bubbling liquid escaping a damaged container. However, it is not as exciting as films may suggest! Nuclear fuel typically comes in a standard set-up in sealed metal tubes that are filled with uranium (fuel) pellets. When this fuel is used up, it comes out the reactor in much the same form, still as a solid in sealed metal tubes, which contains the radioactive material. This is called high-level waste, as it still contains very high concentrations of radiation, despite having often spent 3-5 years generating power in a reactor. This un-recycled, high-level waste is stored in a safe and permanent repository, as it can remain

radioactive for hundreds of thousands (if not, millions) of years. In addition to this high-level nuclear waste, there are also low-level nuclear waste by-products that are generated by such power plants, and this must also be safely handled, transported and stored. The half-life of this low-level waste is much lower and may be neutralized fully within a few decades. Shockingly, most reactors only extract 3-5% of the potential energy from the nuclear fuel before it is deemed “nuclear waste” and replaced with fresh, maximum-efficiency fuel. Given that uranium and other radioactive elements are finite resources on our planet, and also considering the long-term dangers that un-recycled nuclear waste poses to future generations such as accidents at disposal sites or during transportation, leakage, seismic activity, theft and terrorism, it would be very helpful if we could somehow recycle or reuse the waste.

CAN WE RECYCLE NUCLEAR WASTE?

Despite the United States taking a stance against reusing nuclear waste, it certainly can be recycled. In fact, major nuclear countries like France and Japan regularly recycle their nuclear waste, allowing them to get the most out of their resources. This also minimizes the volume of potentially toxic waste they need to store for millennia to come. Before we can get into the details of how nuclear waste is recycled, it needs to be understood how nuclear fuel is initially spent and the transformations that occur in the nuclear material.

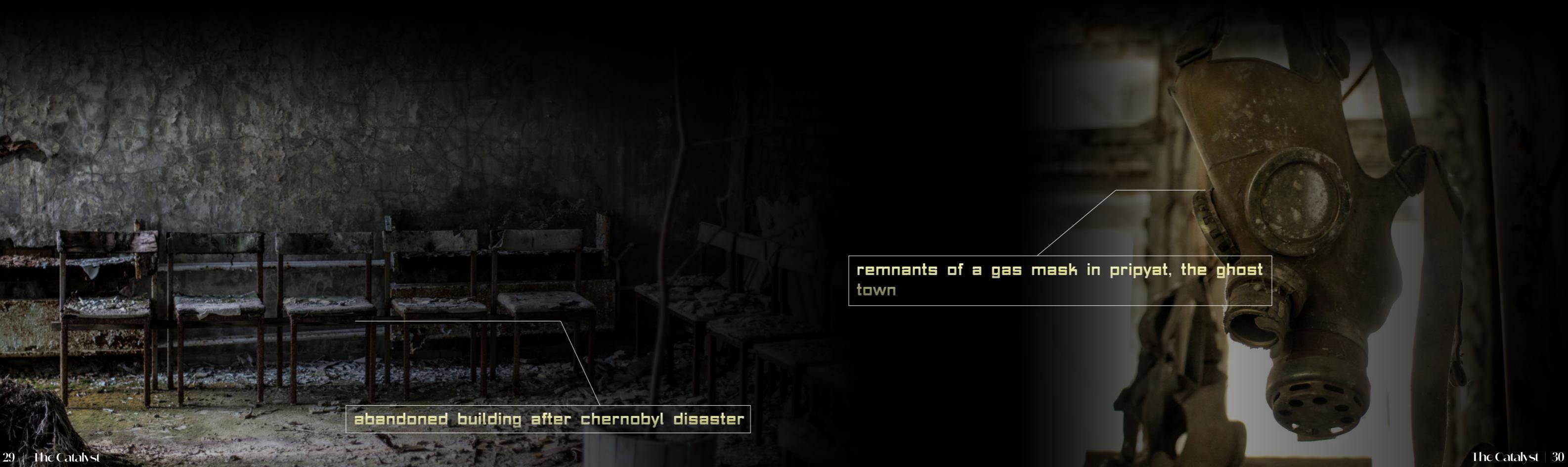
Approximately 11% of the world's power comes from nuclear power plants, and more are being built every

year. All reactors use nuclear fission to generate power, and uranium is the most common radioactive element used for this process. Natural uranium found in the Earth's crust exists as different isotopes, including U-238, U-235 and U-234. These isotopes differ in the number of neutrons found in the nucleus. U-235 is a particularly special isotope, as it is the only naturally occurring material on Earth that is fissile, meaning it can be readily split apart to release large amounts of energy.

When natural uranium is mined, it is typically enriched, which raises the concentration of U-235 from about 0.7% of the uranium's composition to 3-5%. Low-enriched uranium ranges from 1-5% U-235, high-enriched uranium ranges up to 20%, and weapons-grade uranium is up to 90% U-235! When enriched uranium is put

into the nuclear reactor, a controlled chain reaction is set off. In essence, a neutron is smashed into a uranium nucleus, causing it to split, which projects out even more neutrons. These scattered neutrons go on to split other atomic nuclei, thus causing the chain reaction.

Each time an atom is split, it releases a tremendous amount of energy and heat, which (simply put) produces steam that moves turbines, thus producing energy!



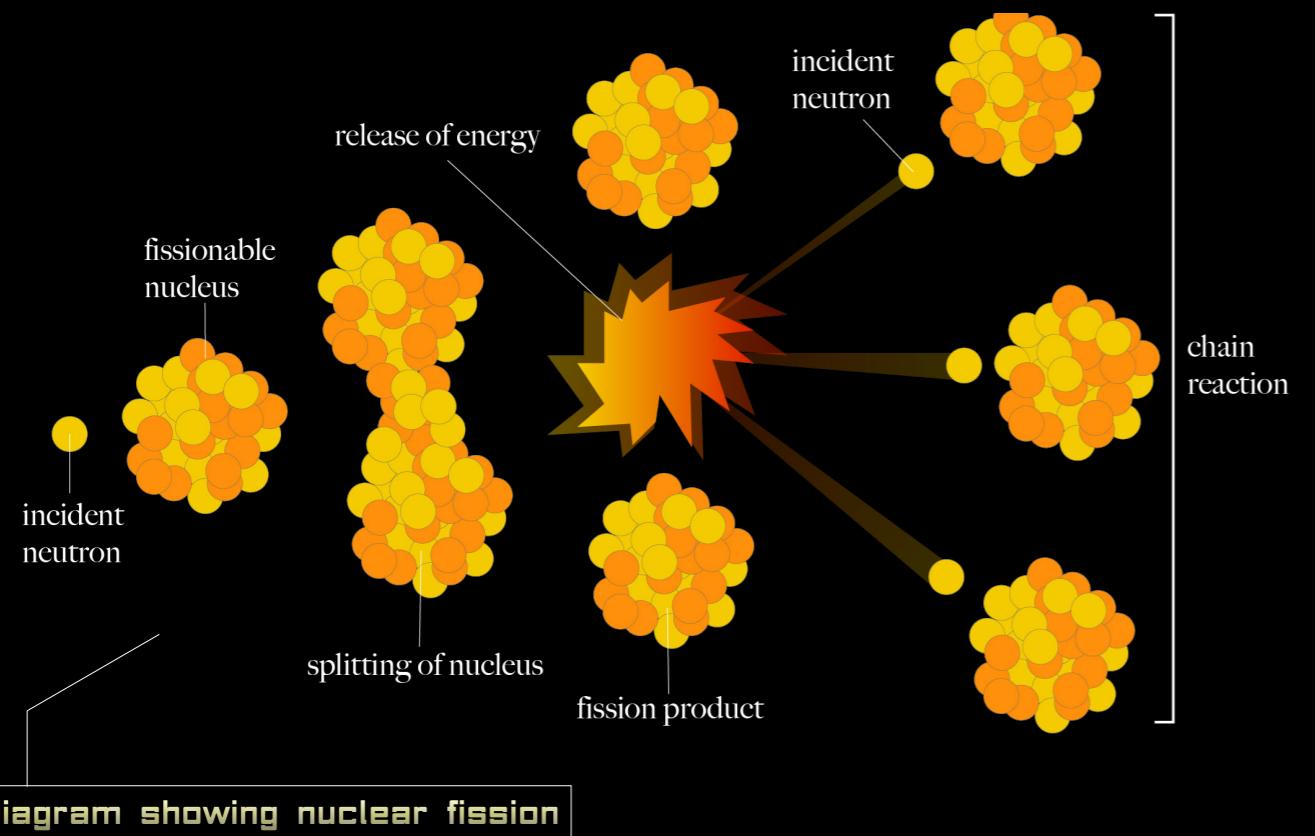


diagram showing nuclear fission

Now, once the U-235 is used up, there is still a large amount of U-238 in the nuclear fuel, but it is weakly radioactive in comparison to its other isotopes. In the past, this fuel was seen as "nuclear waste" and had to be dealt with, but U-238 is a very fertile isotope, meaning it welcomes neutrons to its nucleus, at which point it becomes U-239 (92 protons, 147 neutrons). However, thanks to beta decay in radioactive isotopes, that extra neutron will split into a proton and an electron, thus becoming neptunium-239 (93 protons, 146 neutrons). Within two days, another beta decay will occur, resulting in Pu-239, a plutonium isotope (94 protons and 145 neutrons). Pu-239 is another fissile isotope, though not a naturally occurring one. That plutonium-239 behaves in a similar way to U-235 and can be cycled back into the energy generation process of the power plant, rather than being discarded with the other waste, i.e., fission products.

A fuel cycle is the path that nuclear fuel takes as it moves through a nuclear reactor. A once-through fuel cycle consists of the nuclear fuel (uranium) being used once and then all the spent uranium - including a large amount of U-238, plutonium and fission products - is stored as waste. In a closed fuel cycle, a recycling plant separates the fission products from the usable uranium and plutonium products. The usable fuel in its various forms is re-enriched (in the case of uranium) and put back into the nuclear reactor for further energy generation. Only the fission products are sent to medium-term storage as waste. Finally, in a breeder fuel cycle, these "fast" reactors have extra neutrons flying around inside and can get the most energy out of the uranium fuel resources. The breeder reactor can generate more fissile products than it uses, which can then be sent to a recycling plant,

and subsequently used in normal reactors for maximum resource efficiency. The cost and infrastructure of breeder reactors is high, and the expertise and experience in this field is low, but it creates the least amount of nuclear waste, and can legitimately be considered a sustainable form of nuclear energy.

THE FUTURE OF RECYCLING NUCLEAR WASTE

As a finite resource, it is in our ever-growing interest to discover new, more efficient ways to reuse our nuclear waste. Recent studies by engineering researchers at Texas A&M University have, for example, devised a simple, proliferation-resistant approach for separating out different components of nuclear waste via a one-step chemical reaction. The result is the ability to form crystals containing evenly distributed leftover nuclear fuel elements. Scientists have had some success with separating uranium, plutonium and neptunium. However, these methods have been very complex and have had limited success at separating americium.

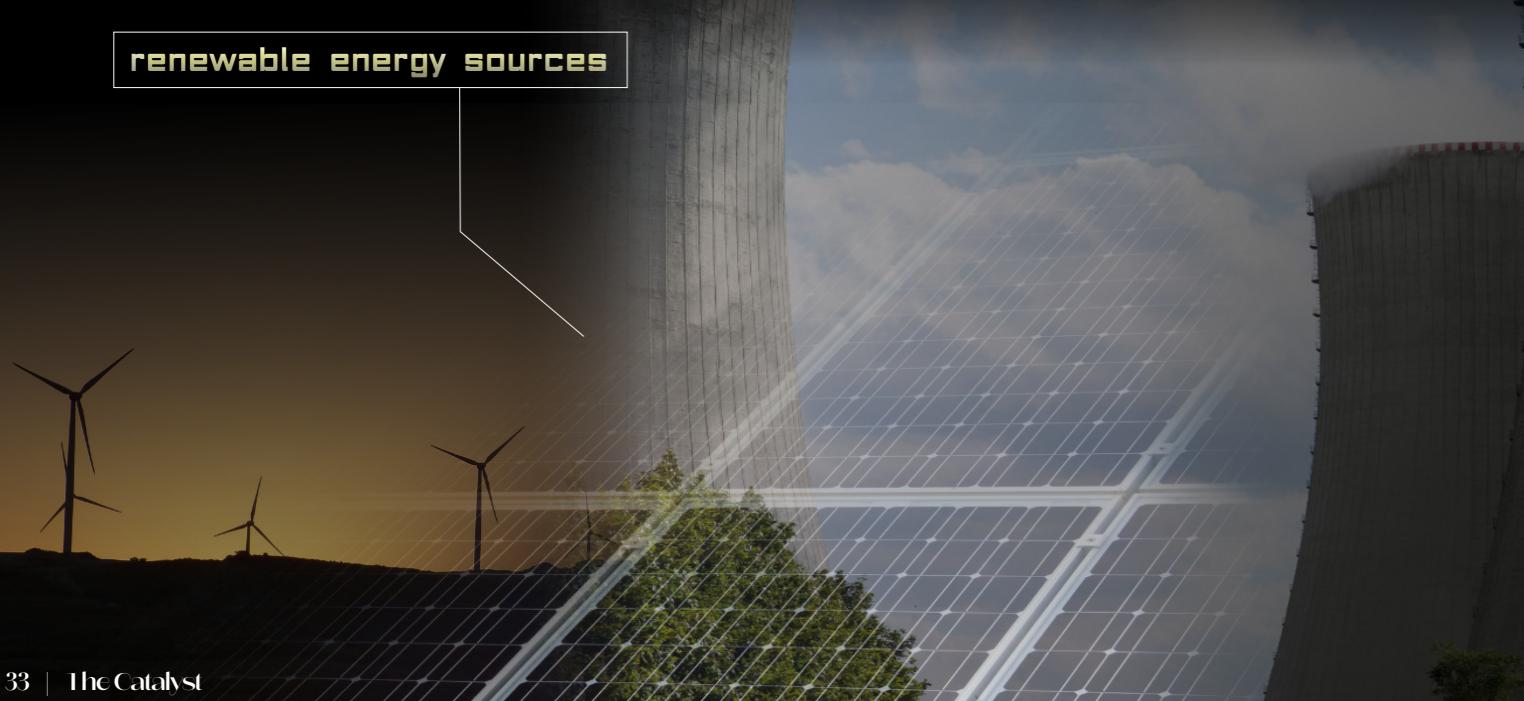
From earlier studies, the researchers knew that at room temperature, uranium forms crystals in strong nitric acid. Within these crystals, uranium atoms are arranged in a unique profile -- a central uranium atom sandwiched between two oxygen atoms on either side, by sharing six electrons with each oxygen atom.

nuclear power plant

“We immediately realized that this crystal structure could be a way to separate out plutonium, neptunium and americium since all of these heavy elements belong to the same family as uranium,”

Burns said, who led the study. The researchers hypothesized that if plutonium, neptunium and americium assumed a similar bonding structure with oxygen as uranium, then these elements would integrate themselves into the uranium crystal.

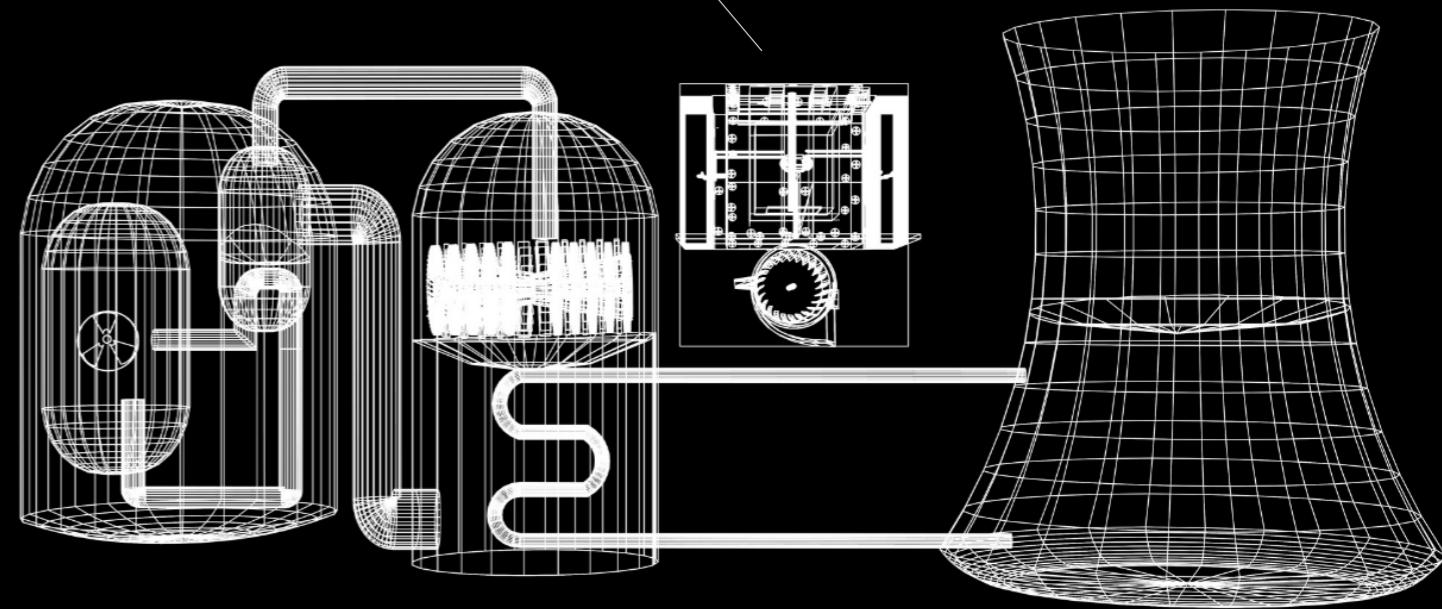
renewable energy sources



They prepared a surrogate solution of uranium, plutonium, neptunium and americium in highly concentrated nitric acid at 60-90 degrees Celsius to mimic dissolving of a real fuel rod in the strong acid. They found that when the solution reached room temperature, as predicted, uranium, neptunium, plutonium and americium separated from the solution together, uniformly distributing themselves within the crystals. Burns noted that this simplified, single-step process is also proliferation-resistant since plutonium is not isolated but incorporated within the uranium crystals.

The success indicated that reprocessed fuel generated from this chemical reaction can be used in future generations of reactors, which would not only burn uranium like most present-day reactors, but also other heavy elements such as neptunium, plutonium and americium.

nuclear reactor diagram



In addition to addressing the fuel recycling problem and reducing proliferation risk, our strategy will drastically reduce nuclear waste to just the fission products whose radioactivity is hundreds rather than thousands of years. It was also noted that the simplicity of their recycling approach makes the translation from lab bench to industry more than feasible!

Nuclear energy is theoretically one of the most sustainable and low-waste options for energy production. The nuclear waste produced in this process has been a problem in the past, but there are now multiple options for recycling and reuse. Advanced facilities and highly skilled workers are required,

but what is most needed is the willingness of nuclear nations to invest fully in recycling infrastructure and reduce the need for long-term, high-level waste repositories that will remain a potential threat for hundreds of thousands of years!

Grignard but DIFFERENT.



Author: Sofia Schönauer



Grignard reagents are commonly used organometallic compounds of the general formula R-MgX. They are synthesized in inert conditions from an alkyl or aryl halide and metallic magnesium in an ether solution (i.e. THF, diethyl ether). Grignard reactions are particularly useful as they create nucleophilic alkyl or aryl groups – “carbanions” – because of the polarity of the ($\delta-$) carbon-magnesium ($\delta+$) bond. They require air-sensitive conditions for storage and reaction alike, due to their reactive nature towards water and oxygen. The discovery of these Grignard reagents as an activation step in carbon-carbon bond formation was awarded the 1912 Nobel Prize in Chemistry to Frenchman Victor Grignard.

In November 2021, a new and revolutionary form of the Grignard reagent was discovered by a Japanese research team at Hokkaido University, which eliminates the need for air-sensitive reaction conditions when handling the organometal. Upon consideration of the financial and environmental factors which go hand in hand with dry solvents, strict temperature and inert gas conditions, and long reaction times, a mechanochemical synthesis of Grignard reagents in paste consistency was proposed.

A standard set-up for a solution-based Grignard reaction requires a complex construction allowing the maintenance of an inert atmosphere, the addition of an electrophile without disrupting the former, as well as dry solvents,

which often carry a high economic or labor cost. In comparison, the new design requires just a mechanical ball mill. In ambient conditions, the Grignard reagents can be produced in the same container and reacted without the need of any measures.

The research team found this method to work for a broad range of reactants. Supporting the underlying premise, many combinations of aromatic, aliphatic or para-/ortho-substituted aryl bromides as nucleophile, and aldehydes or ketones as electrophile gave good reaction outcomes. Other factors were also investigated to establish a causal relationship between the method and the results. For example, when using liquid substrates under the same conditions, little to no product was formed.



This establishes that mechanical agitation during the milling is key to the formation of the nucleophile. When run under a nitrogen atmosphere, the ball mill method did not increase reaction efficiency compared to the original set of conditions, proving the effort of creating this inert reaction environment unnecessary.

In addition to uncovering this phenomenon, an array of other factors with possible effects on the reaction outcome were considered and tested

for. **A heat gun creating temperatures of 70° C inside the mill allowed even for poorly soluble aryl halides to react**, as the kinetic energy provided can aid in the mixing process and thus incorporation of the magnesium into the carbon-halogen bond. When comparing halogens, bromine, chlorine and iodine gave yields in descending order, although all above 70%. The reproducibility on larger dimensions was also confirmed by a reaction on a gram scale, coming close to the original yield.



The main reason why this set-up allows for a Grignard reaction to take place is attributed to

mechanochemistry. This term covers unusual chemical reactions caused by mechanical energy and dates back to the 1890s with the use of mortar and pestle for organic synthesis. It is predominantly used in the synthesis of nanomaterials as it eliminates the need for unwanted solvents in the reaction. The principle behind mechanochemistry is quite simple: the energy required to break intramolecular and intermolecular bonds is not provided

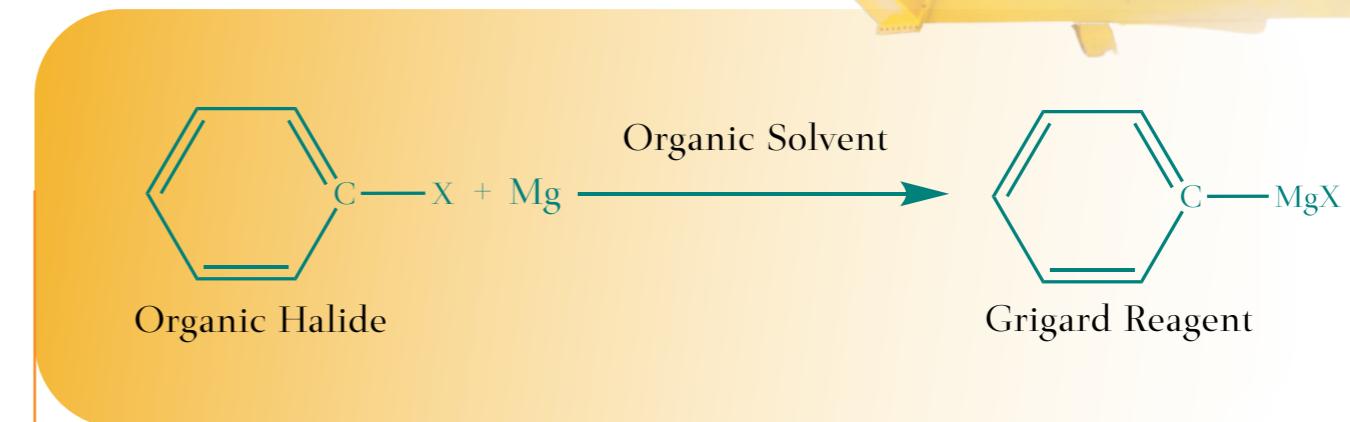


Figure 1: Grignard Reaction Scheme, where X is a halide

by heat and the mixing of substrates is not aided by solubility in a solvent.

Both of these requirements are met by mechanical force exerted from the ball mill, for example.

In addition, the benefits of good yield, faster reaction time and no need for solvent, among others, make this method worthwhile.



This new method of carrying out Grignard reactions, alongside more and more applications for mechanochemistry in organic synthesis that are being discovered, have incredible effects on industrial sectors. The use of this process in the food, pharmaceuticals and materials industry (to name a few) can revolutionize the quality of products, as well as the safety and ease of production by eliminating the possibility for toxic solvents while maintaining a good atom economy. Organic chemistry, as we've known it for over a century, is thus innovated and will continue to do so as mechanochemistry is integrated and researched more.



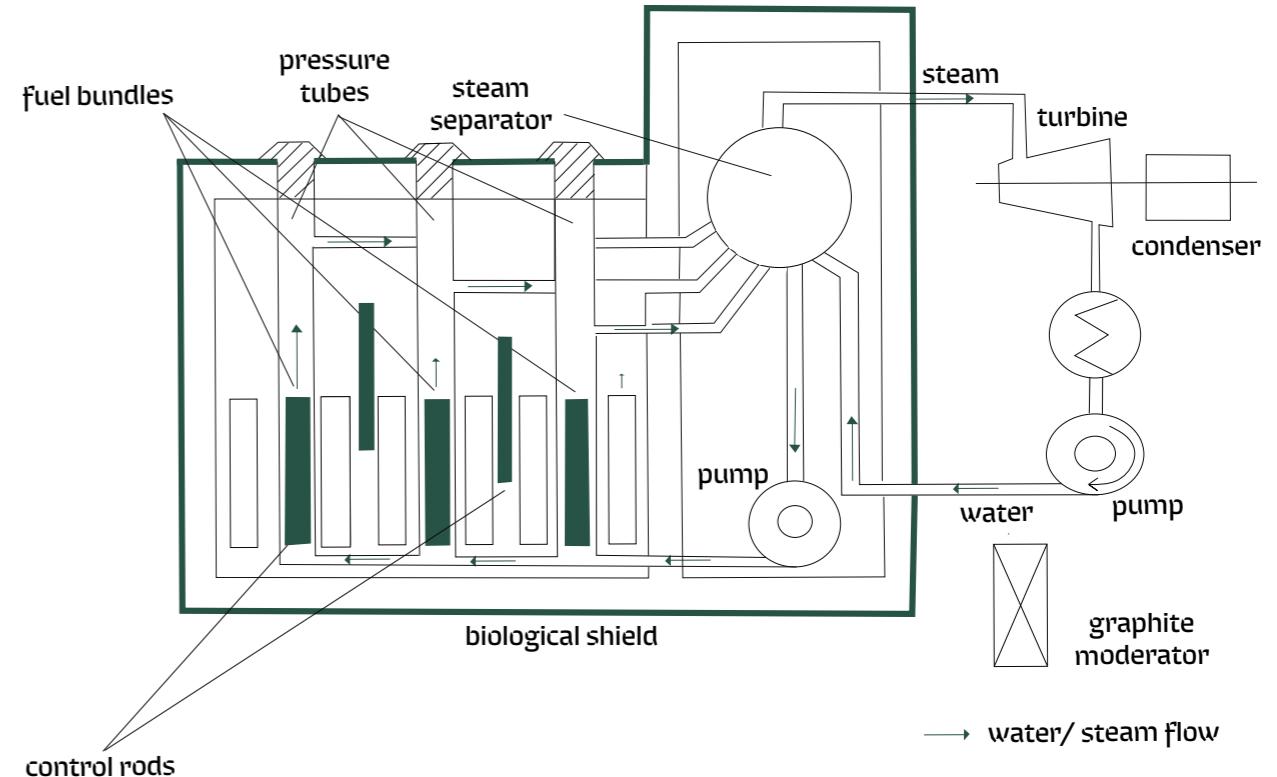


Fig 1. Diagrammatic representation of RBMK 1000

The Chernobyl accident in 1986 was a nuclear disaster that occurred in the Chernobyl nuclear power plant. The power plant was located in the North of Ukrainian SSR in the Soviet Union. It is one of the most devastating nuclear accidents in history.

The Chernobyl power complex had four nuclear reactors made up of an RMBK design (Figure 1).

Due to a loss of main electrical power, on April 26th 1986, the long turbines at Chernobyl 4 were tested to determine how they would spin and supply power to the main circulating pumps. The automatic shutdown mechanisms were disabled before the test. During the test, the reactor was extremely unstable as the operator moved to shut the reactor down. As the control rods were inserted into the reactor, the power significantly intensified. This resulted

in a surge of pressure and the control rods therefore jammed. The core of the reactor then filled with intense steam, resulting in two catastrophic explosions, the second one releasing hot graphite and fragments from the fuel channels. Several fission products were released through this steam explosion, resulting in the largest amount of radioactive release seen in history. Hundreds of radioactive elements were released as the reactor exploded, many however decaying quickly, as they were only short lived.

The accident resulted in the death of 30 people, most of them being fire-fighters and operators passing as an immediate result of the explosion. A further 28 people departed due to Acute Radiation Syndrome (ARS) during the weeks that followed. The Chernobyl accident is the only known case of radiation related deaths as a result of a nuclear power plant explosion.



The most significant radiation dose administered to the public was through the radioactive isotopes: long lived caesium-137, strontium-90 and short lived iodine-131. Strontium-90 and caesium-137 are still present in the areas surrounding Chernobyl and are linked to higher cancer rates. Caesium-137 is a radioactive isotope that emits beta particles and gamma rays. With a half-life of 30.7 years and formed through nuclear fission of uranium-235, it has the ability to travel extremely long distances and to undergo beta decay to form barium-137m, and gamma decay to form the ground state of barium-137m. Exposure to caesium-137 can result in burns, Acute Coronary Syndrome (ACS), and in high enough doses, death. The high-energy gamma radiation present causes the association between caesium-137 exposure and increased risk of developing cancer. Inhalation causes it to be distributed directly to muscle tissue causing an even greater risk of tumours.

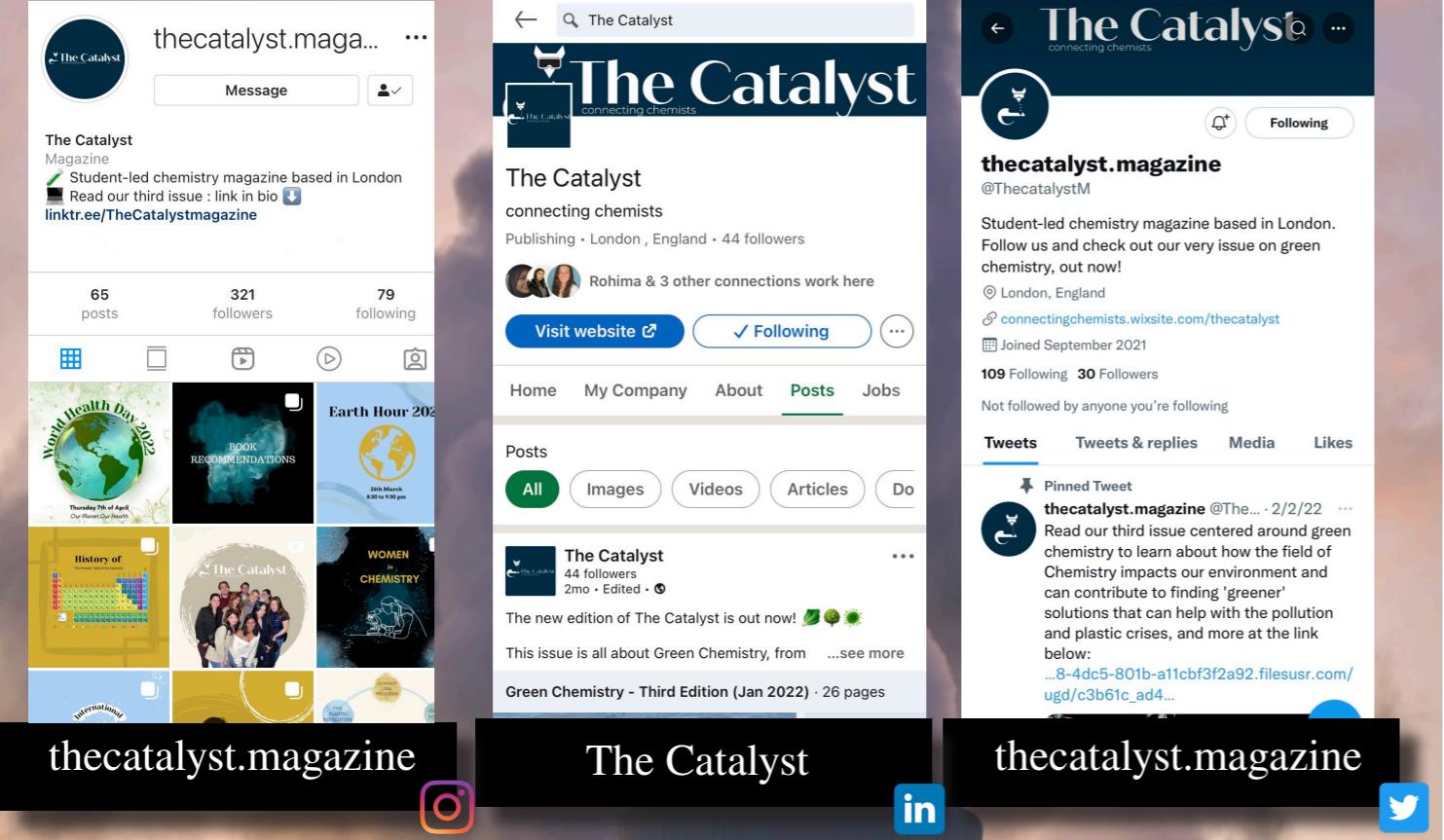
Strontium-90 is a radioactive isotope, formed through nuclear fission of uranium-235, uranium-233 and plutonium-239 which has a half-life of 28.8 years. Most strontium is stable in its natural state. ^{90}Sr is the most hazardous isotope of strontium and undergoes β -decay to yield the radioactive isotope, yttrium-90. Yttrium-90 then gives off radiation to form zirconium-90, a stable atom.

The risk of exposure to strontium-90 is dependent on the duration and amount of radiation. Strontium-90 is classed as a human carcinogen, more specifically associated with leukaemia and bone cancer upon human exposure to food and water contaminated with it. This happens as strontium-90 is deposited throughout the body and emits its β -radiation there.

Iodine-131 is a radioactive isotope of iodine that has a half-life of 8 days. It is a product of the nuclear fissions of uranium and plutonium, undergoing β -decay rapidly followed by γ -decay to form the stable isotope xenon-131. Iodine-131 is associated with an increase in thyroid cancer, specifically in children. In the years that followed after the accident, 1800 cases of thyroid cancer were documented in children aged 0 to 14 years old at the time of the incident, which was far greater than the national average. This is thought to have been caused by the consumption of contaminated cow's milk, as children were exposed to greater relative doses associated with displaying smaller thyroid volumes.

The accident had a lasting impact, with the greatest socioeconomic effects seen on the populations of Belarus, Ukraine and Russia. Hundreds of thousands of civilians were evacuated from contaminated areas and then later relocated. Several international programmes were created to ensure such a nuclear disaster is not repeated: the International Atomic Energy Agency (IAEA) made safety reviews for different types of Soviet reactors and The Convention on Nuclear Safety was created in Vienna. They were implemented, taking caution to ensure such devastating incidents do not happen again.

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The term “hydrogen economy” is used frivolously, but what does it truly mean? Cheaper electricity? Cars that don’t pollute? Sustainable energy? All of these are undeniably attractive propositions, each becoming ever pressing as a necessary reality while our climate crisis develops into a climate catastrophe. But how far out of reach are these truly? Omitting the technology required to render hydrogen fuel useful for consumption, allows us to focus on the problem of acquiring the necessary hydrogen. While this initially appears simple, the quantity of H_2 in our atmosphere is in fact only 0.00005%, an infinitesimal fraction of what we would need. Hence, to produce hydrogen, researchers have turned to our most earth-abundant resource - water - and devised a way to split it! The ability to split water into hydrogen and oxygen seems almost akin to wizardry, but it simply boils down to crucial chemistry that our energy-demanding society yearns for every day.

This reaction requires no further setup than some water, a semiconductor photocatalyst, and sunlight. However, nearly 50 years after it was first achieved by Fujishima & Honda using TiO_2/Pt photoelectrodes, the mechanisms behind this reaction are still poorly understood, and aspects are still being uncovered! This field has seen a constant increase in research interest, as this seemingly simple reaction is more complex than one may believe. Let us then start by examining the process behind it, as we understand it so far.

A semiconductor is submerged in water and solar light is irradiated upon it.

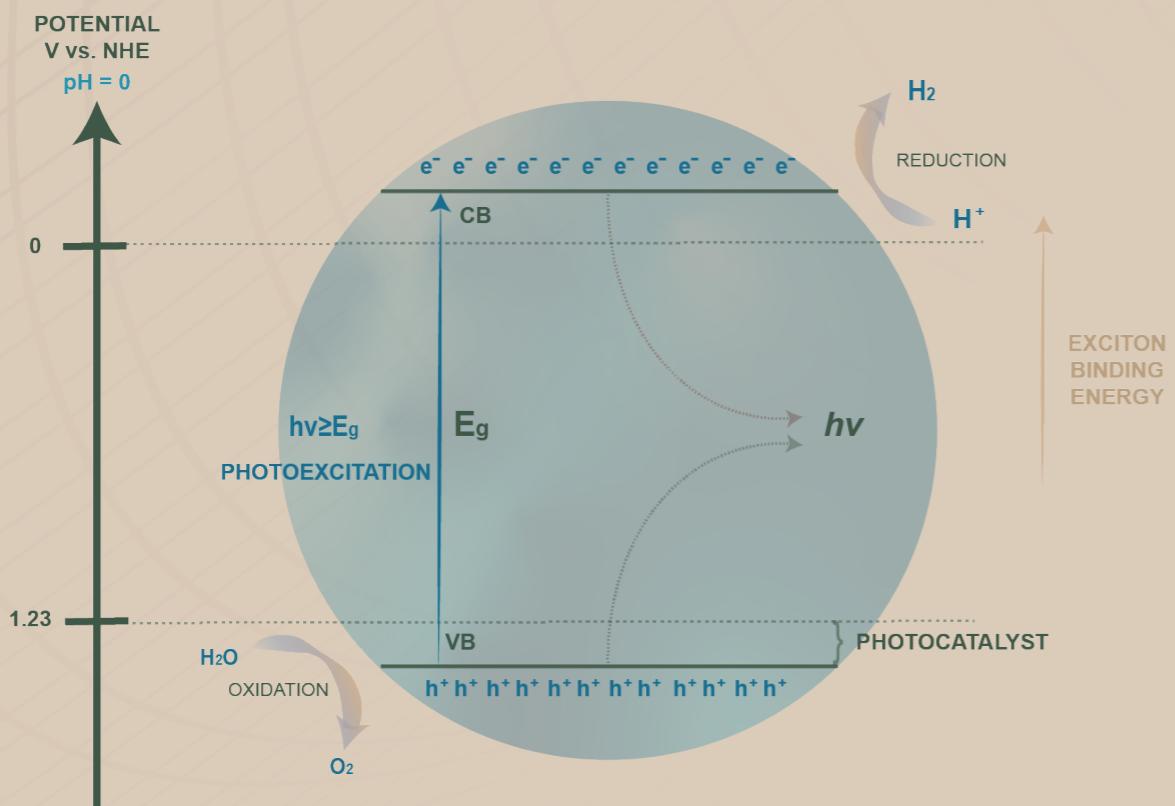


Figure 1. Schematic illustration of a one step photo-excitation in a water-splitting system.

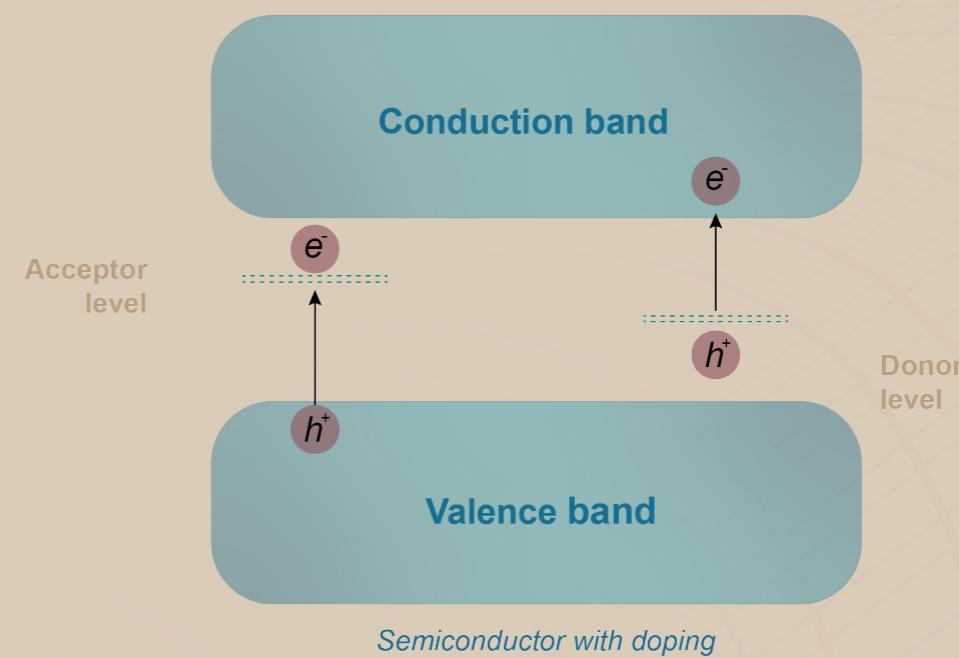


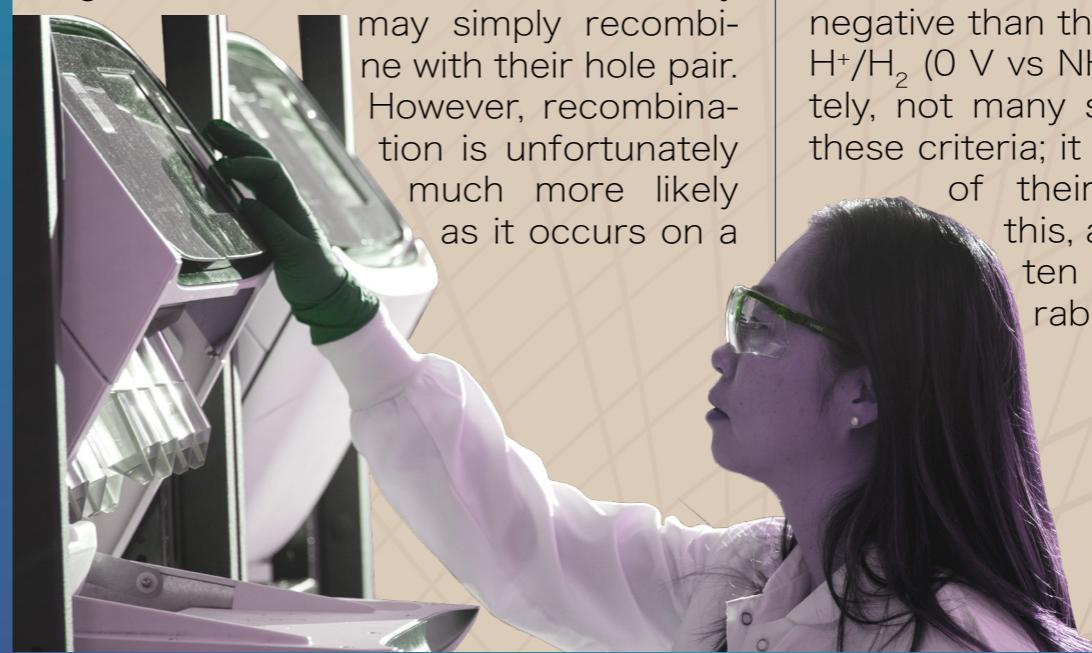
Figure 2. Schematic illustration of the effect of n/p type doping on the band edge position (and Fermi level).

The incident light of adequate energy activates the semiconductor by causing localised electrons in the low-energy valence band (VB) to delocalise, and be promoted to the high-energy conduction band (CB) - the difference between the VB and CB is called the bandgap energy - this is accompanied by the formation of positive electron holes (e^- holes) in the VB. The excited electrons (excitons)/holes may then either travel to the edge of the photocatalyst and react with H_2O in a redox reaction to evolve H_2 (Hydrogen Evolution Reaction (HER)) and O_2 (Oxygen Evolution Reaction (OER)), or they

may simply recombine with their hole pair. However, recombination is unfortunately much more likely as it occurs on a

scale of 10^{-9} s, whereas the chemical reaction is on the order of $10^{-8} - 10^{-3}$ s. It is a fight against attraction.

This setup is clearly only simple from an outside perspective. For it to actually function, the semiconductor must fulfil both kinetic and thermodynamic requirements which drive the decomposition of H_2O . This in part (thermodynamically) means that the VB of the material should have a more positive potential than the oxidation potential of H_2O/O_2 (1.23 V vs. NHE pH 0), and that the CB potential should be more negative than that of the reduction of H^+/H_2 (0 V vs NHE pH 0). Unfortunately, not many semiconductors meet these criteria; it is often that only one of their potentials satisfies this, and if both do, this often results in an unfavourable bandgap energy.



Bandgap energy and structure are hence primordial. Successful water splitting relies on the ability of photo-generated charge carriers to be made and overcome recombination. As solar light is primarily composed of near-infrared & visible light photons, the bandgap energy should reflect this, and therefore fall within the range of 1.8 – 2.4 eV, as this is the energy of the majority of incident photons. Nonetheless, as stated, materials with the ability to perform both sides of the redox reaction often have bandgap energies $>2.4\text{eV}$, closer to 3 eV, meaning that they only absorb UV wavelengths, which represents only about 5% of the incident light, greatly reducing their absorbance efficiency.

To counter this and increase the efficiency of materials, researchers are investigating fine-tuning the physical and chemical structure by way of nanoscale modifications. The first and most common modification is n-/p-type doping, the introduction of a donor (n-type) or acceptor (p-type) impurity into a material. The introduction of such an impurity in the photocatalyst causes additional energy levels to be created. Looking at an n-type semiconductor, the addition of a donor impurity which increases electron density shifts the Fermi level of the VB higher in energy, closer to the CB, reducing the bandgap energy and facilitating electron-hole dissociation. The converse is true for a p-type semiconductor.

On the other hand, to make semiconductors which are incapable of evolving both hydrogen and oxygen viably, an ingenious work around has been developed: Z-scheme heterojunctions. These are constructed by coupling 2 semiconductors, each able to perform one half of the water splitting reaction, separated by a membrane and interconnected by an electron mediator. This allows the protons and electrons generated by the oxidation of oxygen on one end to travel across the membrane and be used for the reduction of hydrogen on the other, permitting the entire process to occur. This also simplifies the separation of the products, but unfortunately leads to greater recombination of charge carriers and decreased photon availability due to the electron mediator, although research is being performed to circumvent this.

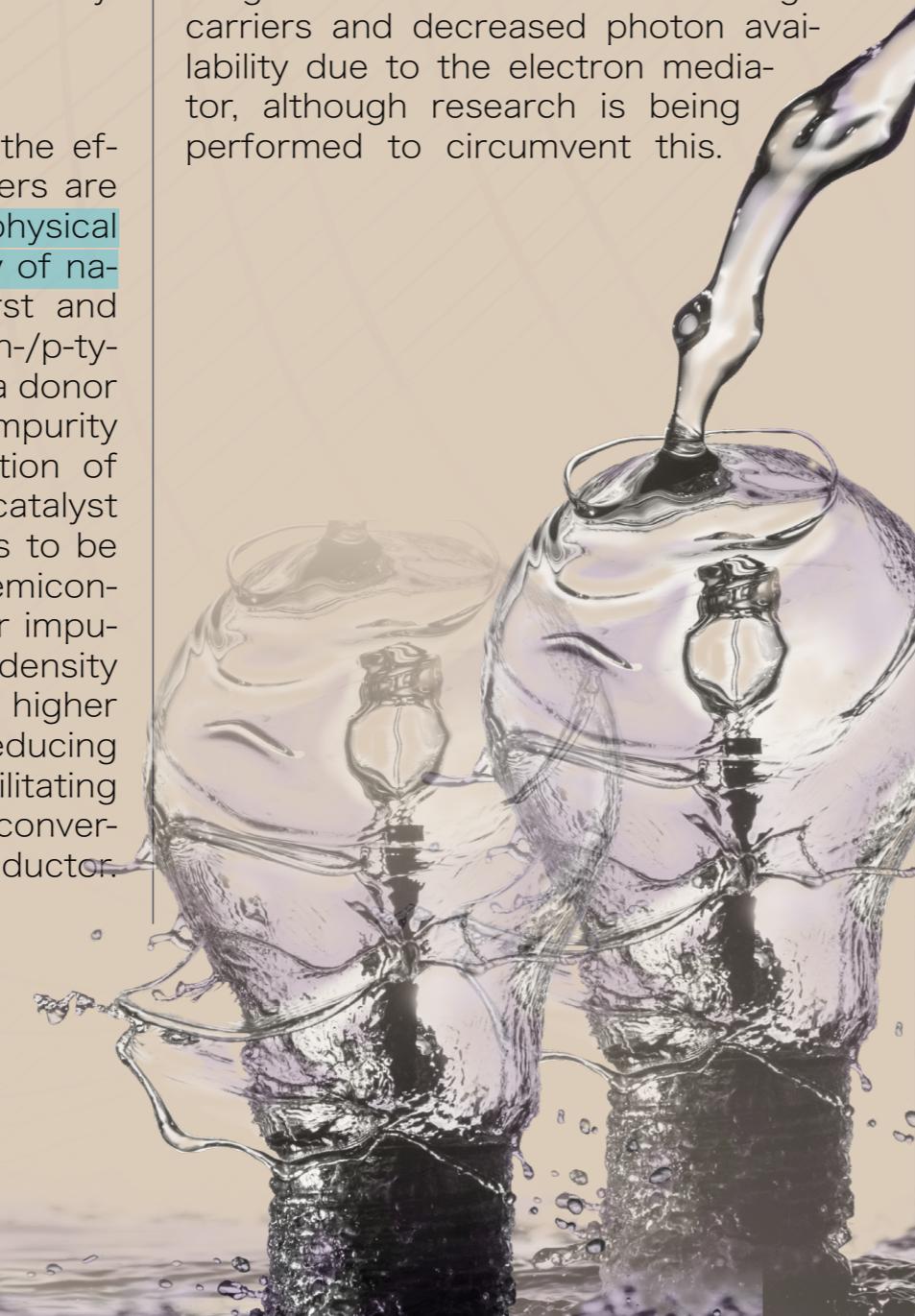


Figure 3. Main challenges associated with the use of photocatalytic materials: (1) redox potential; (2) wavelength light absorption; (3) solar to hydrogen efficiency; (4) (photo-) chemical stability; (5) toxicity; (6) cost/scarcity; (7) material scalability; and (8) fabrication versatility.

Photocatalytic water splitting by semiconductors, especially metal-free ones, evidently provides an attractive solution to produce hydrogen fuel in a sustainable way. Yet there are many challenges which first need to be overcome before this hydrogen economy becomes a reality. Complications and solutions associated with the bandgap have been discussed,

however many other factors are also at play, especially when considering industrial viability. A scalable photocatalyst must achieve at least a 10% Solar to Hydrogen (STH) conversion efficiency, which is not the case of many, as well as have good physico-chemical stability to ensure its use over many cycles. Furthermore, it should ideally be made of cheap, non-toxic, earth-abundant materials, and be synthesised in a relatively simple way so as to not incur extra costs. This is a tall order to say the least, but a material fulfilling all these characteristics would revolutionise our energy capabilities, paving the way towards a more sustainable future.

A powerful tool to explore the atomic and molecular world!



Author: Xiaojian Qu

This is the first part of a series on synchrotron radiation, where you'll discover the beauty of synchrotron radiation and its discovery in history and early applications. I hope you enjoy it!

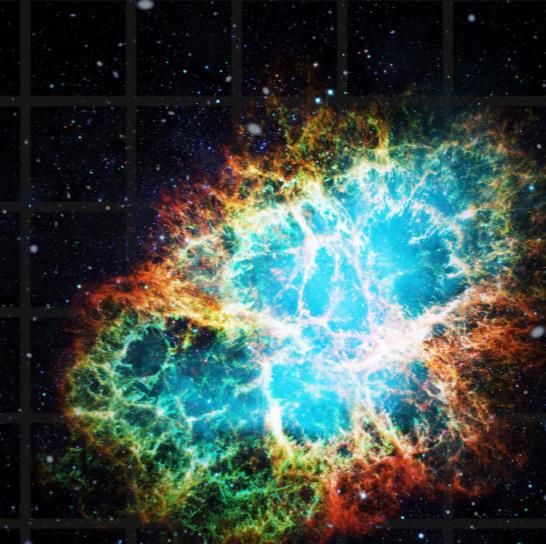
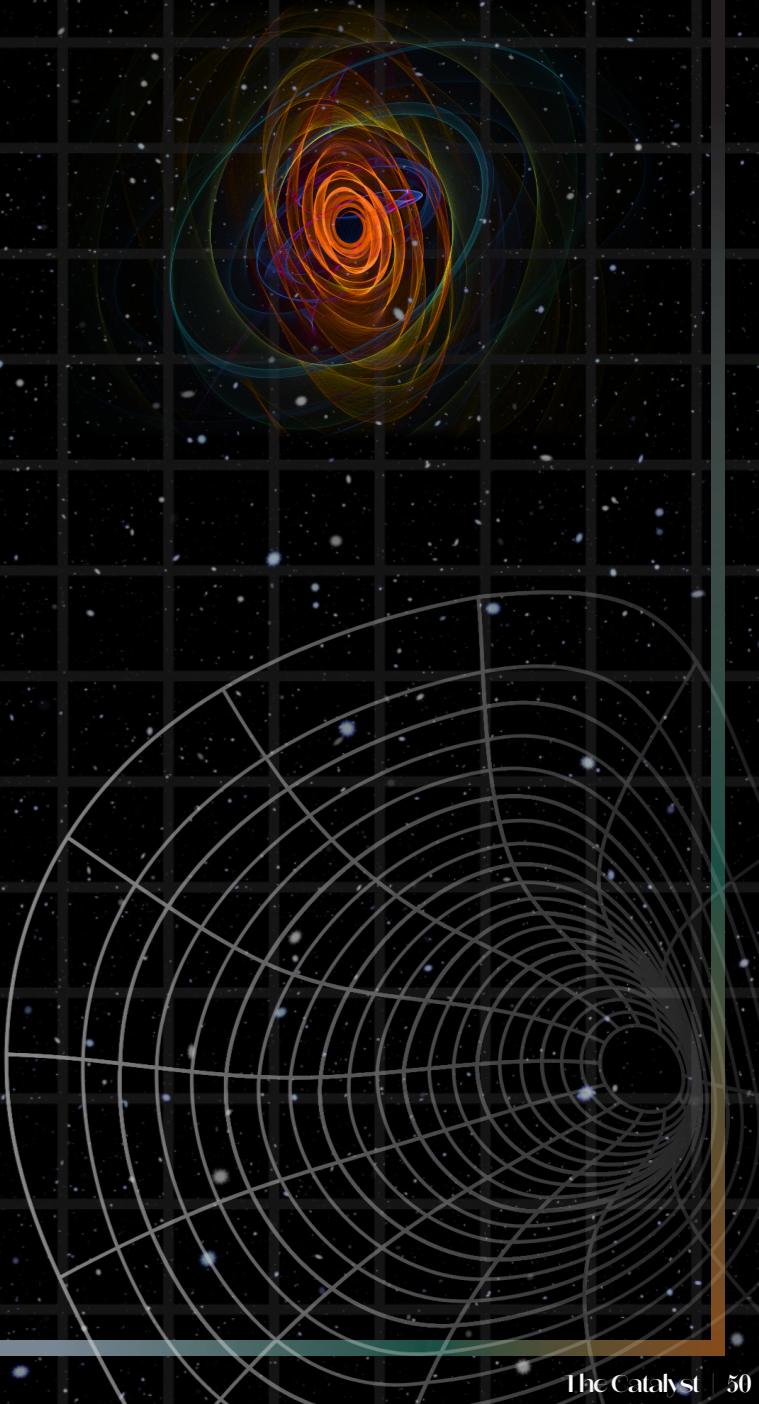


Figure 1. *Crab Nebula*

I bet most of you are not familiar with synchrotron radiation, but you may not realize that you've come across it before. This famous image of the Crab Nebula (*Figure 1*) has been widely seen on television, in magazines and online, as one of the Hubble Space Telescope's most important outcomes. The eye-catching bluish glow from the nebula's central region is actually due to synchrotron radiation!

The Crab Nebula is a remnant of a supernova explosion, which contains the Crab Pulsar at the centre of it. Pulsars are rapidly rotating neutron stars that usually have powerful magnetic fields. At the magnetic field poles, where the field is the most potent, they produce cyclo-synchrotron radiation by the curving motion of electrons. The radiation corresponds to electrons moving as fast as half the speed of light.

When the pulsar spins, synchrotron radiation from the poles changes direction in space with it, like a rotating lighthouse, so periodic pulses can be observed on Earth. You might want to see this magnificent sight for yourself, but synchrotron radiation has a broad spectrum from far infrared to X-rays, and Figure 1 is actually a mosaic image under coloured filters that captures synchrotron radiations by charge-coupled devices. However, you can see it as a grey flare, with binoculars, in good air conditions. Still, you won't be able to see it flickering because it rotates about 30 times a second!



Discovery of synchrotron radiation

I hope the above explanation of the Crab Nebula gave you a taste of the beauty of synchrotron radiation. For centuries, people had seen starlight produced by synchrotron radiation heating ordinary matter from stars or galaxies, without knowing that it essentially resulted from the acceleration of electrons in the large magnetic fields associated with astronomical objects.

The discovery of synchrotron radiation is based on modern electromagnetism and electrodynamics. In 1898, Alfred-Marie Liénard firstly pointed out that an electric charge moving in a circular path should radiate energy. Subsequently, this theory was extended by George Adolphus Schott to provide the background for an electron theory of matter. Their theories and calculations were verified by the world's first successful multi million volt accelerator at the University of Illinois in 1941. Three years later, two Russians, Ivanenko and Pomeranchuk, pointed out that radiation loss is proportional to the fourth power of energy for relativistic electrons. Thus, radiation loss could place an energy limit on betatron design. Their predictions were proved by J. P. Blewett, who showed that the orbit contraction was consistent with the radiation loss in a 100 MeV betatron.

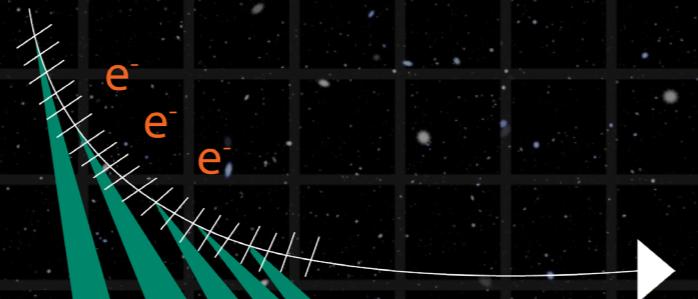


Figure 3. The synchrotron radiation (green) is tangent to the beam orbit (white).

In 1946, the synchrotron radiation (Figure 3) was observed for the first time as a very bright spot of light through a glass vacuum chamber of a 70 MeV synchrotron at the General Electric Research Laboratory. Synchrotron radiation intrinsically has nothing to do with synchrotrons and, an acceptable explanation of its name is that the magnetic field that bends the particles around, increases with time and is synchronized to their increasing kinetic energy.

As the historian of science, Robert P Crease once said, „Synchrotron radiation was initially regarded as a nuisance because, beyond a certain point, any additional energy put into the electrons would be promptly radiated away“. Physicists spurned synchrotron radiation as it limited the power of electron accelerators. However, synchrotron radiation will be justified in the following decades because scientists found that it could be used as a source of intense and finely tunable X-rays in chemistry, biology, and material science research.

Synchrotron as an X-Ray source

X-rays were initially discovered by W.C. Röntgen in 1895, who found their capability of passing through the human body. In 1952, the female scientist Rosalind Franklin took the X-ray diffraction pattern of DNA with her graduate student Raymond Gosling in King's College London. This was the first significant discovery since the advent of X-ray imaging. James Watson and Francis Crick copied this picture without the author's permission and used it to calculate and build the world's first DNA model. However, further X-ray diffraction studies were hampered in the 1960s because the X-ray tubes were limited, as the light was emitted in all directions, with no possibility of focusing it or making the rays parallel. This light was also only intense at particular wavelengths, which restricted its use, particularly in the field of spectroscopy.

At the same time, scientists recognised that synchrotron radiation could be applied to overcome the weakness of X-ray tubes. As a result, the first generation of synchrotron-radiation light sources are parasitic facilities because the accelerators were built and usually operated primarily for high-energy or nuclear physics. Moreover, the storage rings were electron-positron colliding-beam machines that provided the highest possible collision rates without blowing up the beams, a condition that generally meant low beam currents and energies, which disadvantaged the output of synchrotron radiation. Thus, the second-generation light source was built dedicatedly for producing synchrotron radiation. Although the second generation of light sources is a million times brighter than X-ray tubes, crystallography experiments in the 1970s were still hungry for brighter X-rays to maintain sufficient angular resolution and to resolve closely spaced diffraction spots.



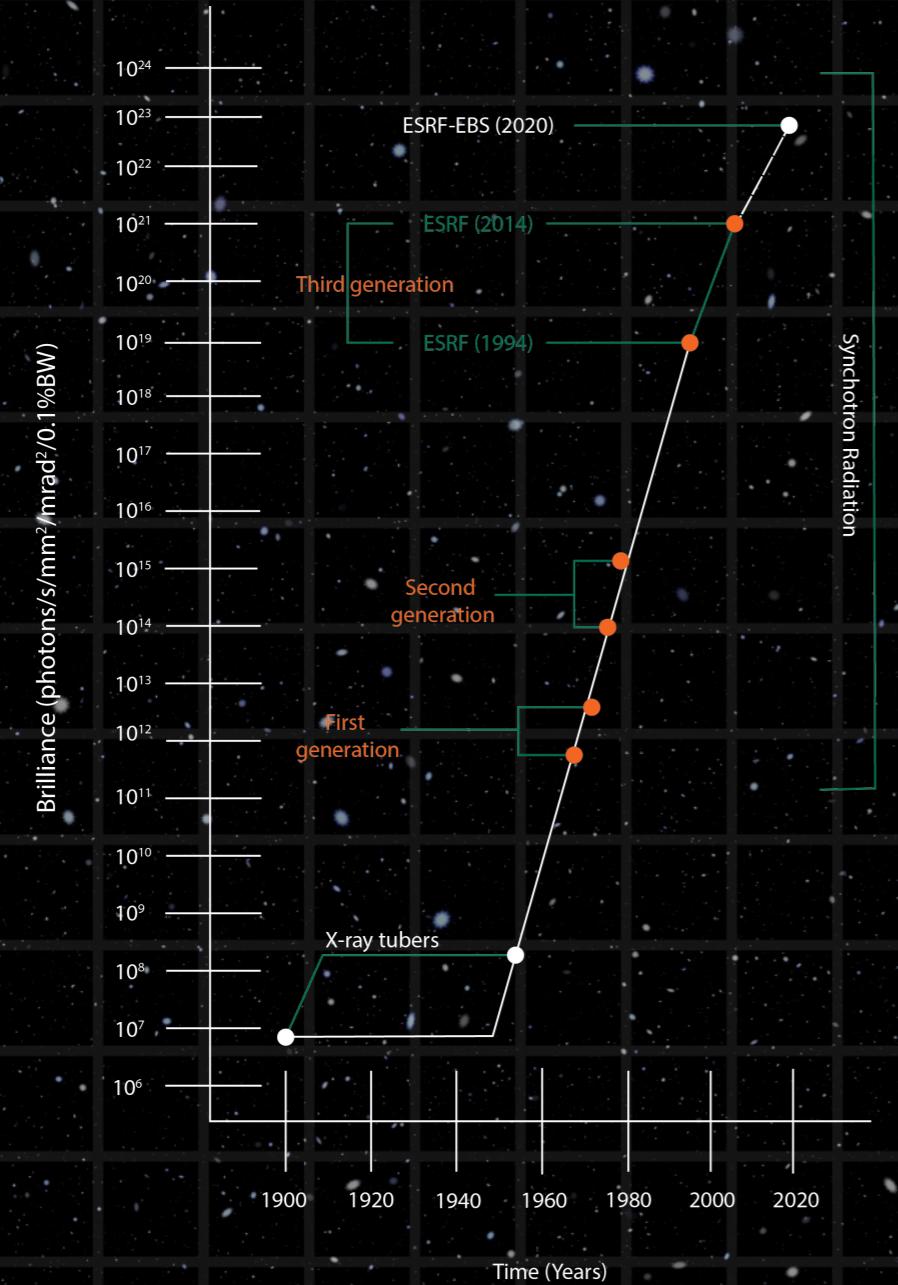


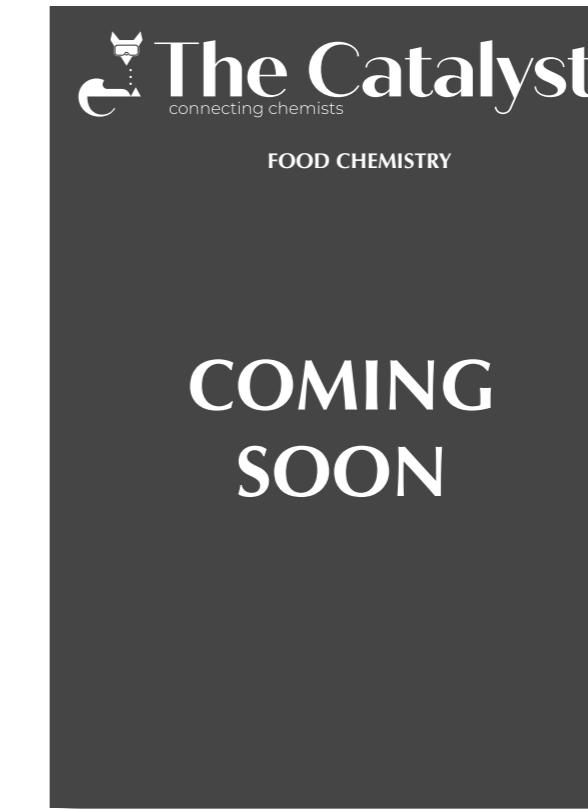
Figure 4. The development of synchrotron light source

In 1994, the European Synchrotron Radiation Facility (ESRF) was the first third-generation x-ray source opened to the public (Figure 4), which is 100,000 times brighter than the last generation. In addition, the storage ring in ESRF contained longer straight sections for applying insertion devices (undulators and wigglers), which guaranteed a significantly higher brightness and a considerable degree of spatial coherence. The Extremely Brilliant Source (EBS), opened early this year, was announced as the fourth generation light source,

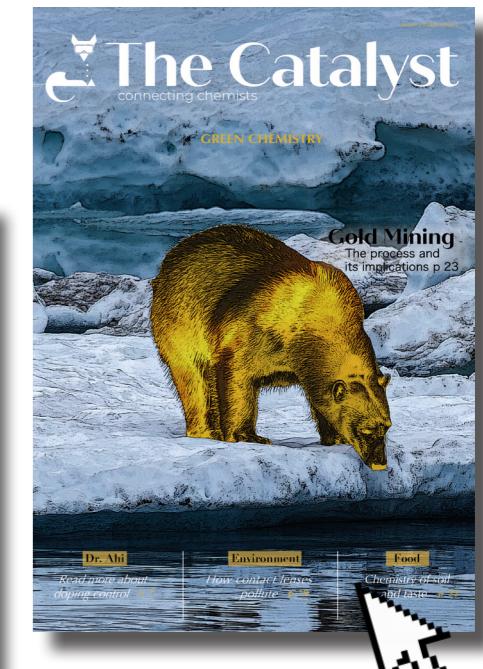
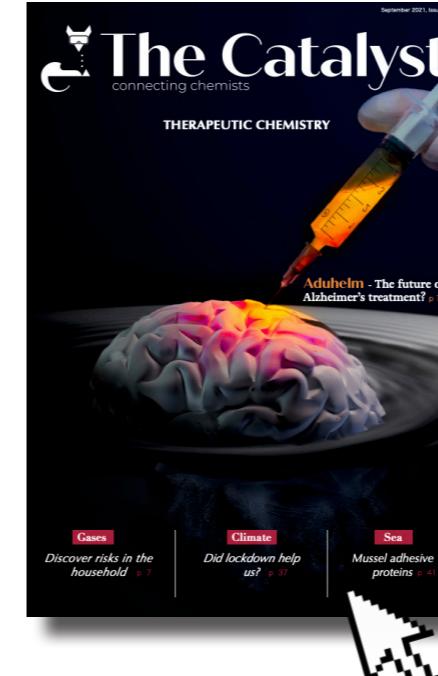
and it upgraded the lattice of ESRF to a hybrid multi-bend achromat. However, it is only a hundred times brighter than its predecessor, so academics consider it a third and half generation source.

I hope synchrotron radiation has been interesting so far! In the second half of this series, you'll learn about the anatomy of a typical third-generation synchrotron radiation source and its future! See you in a few months!

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