Searching for Viable Paths to Nuclear Fusion Energy

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Colloquium Department of Physics
The University of Ariona
Friday August 26th, 2022

Abstract

Nuclear fusion energy powers the Sun. The objective of harnessing this abundantly available potentially non-radioactive source of energy on Earth has widespread interest. However, the zeroth-generation large ITER plasma fusion reactor under construction requires nuclear-weapon tritium cycle generating high energy neutrons.

My personal research interests are focused on fusion concepts relying on alternative light isotope nuclear reaction cycles that sidestep the equilibrium plasma conditions which are beyond near-future technology reach. In this talk I will discuss: nuclear fusion in general; highlight ITER at cross-roads; and introduce: Muon catalyzed nuclear fusion; Laser driven proton acceleration used to spark micro-explosion fusion; and laser driven coherent plasmon field induced fusion. The three modern high tech approaches are world-wide under active study supported by both private and government sponsored research programs.

My fusion credentials

- 1973: PhD from Frankfurt University with specialty in **theoretical nuclear physics**
- 1978, 1985 – 1992: Muon-catalyzed fusion
- 2011 – 2015: pB fusion and lasers
- 2021 – present: Moving into plasmonic fusion

nature COMMUNICATIONS

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Fusion reactions initiated by laser-accelerated particle beams in a laser-produced plasma

C. Labaune[1], C. Baccou[1], S. Depierreux[2], C. Goyon[2], G. Loisel[1], V. Yahia[1] & J. Rafelski[3]

The advent of high-intensity-pulsed laser technology enables the generation of extreme states of matter under conditions that are far from thermal equilibrium. This in turn could enable different approaches to generating energy from nuclear fusion. Relaxing the equilibrium requirement could widen the range of isotopes used in fusion fuels permitting cleaner and less hazardous reactions that do not produce high-energy neutrons. Here we propose and implement a means to drive fusion reactions between protons and boron-11 nuclei by colliding a laser-accelerated proton beam with a laser-generated boron plasma. We report proton-boron reaction rates that are orders of magnitude higher than those reported previously. Beyond fusion, our approach demonstrates a new means for exploring low-energy nuclear reactions such as those that occur in astrophysical plasmas and related environments.

Ref.TH.2679-CERN

受入
79- 7- 143
高工研図書室

HYDROGENIC MESOMOLECULES AND MUON CATALYZED FUSION

J. Rafelski

CERN -- Geneva

A B S T R A C T

Hydrogenic mesomolecules are discussed with particular emphasis on their rôle in the μ catalyzed fusion process. Recent theoretical and experimental evidence for weakly bound mesomolecules ddμ and dtμ derived from resonant mesomolecular formation and its dependence on the temperature is described. The fate of the muon stopped in dense hydrogenic target is followed as well as that of a muon sticking to the fusion product.

Lectures at the International School of Physics of Exotic Atoms, Erice
25 March -- 5 April 1979

Ref.TH.2679-CERN
8 June 1979

There are many different fusion reactors natural and (planned) manmade

Can we facilitate nuclear fusion via a different path as compared to early Universe Big Bang nucleosynthesis (BBN) or stellar core reactors?
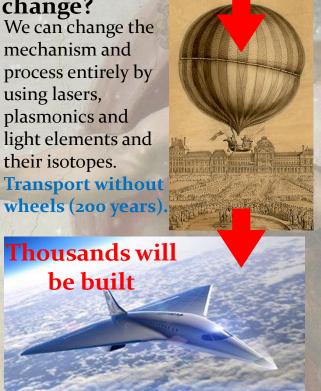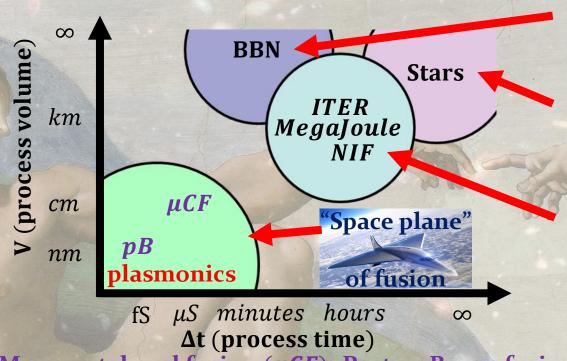
What can we change?

We can change the type of nuclear fusion fuel used and method of confinement e.g. replacing gravity force with magnetic fields. Result: Development of deuterium-tritium fusion reactor for past 70 years. **This is like the evolution of the chariot (1,000s of years).**

We can change the mechanism and process entirely by using lasers, plasmonics and light elements and their isotopes. **Transport without wheels (200 years).**

Only one exists

Thousands will be built

There are many different fusion reactors natural and (planned) manmade

Can we facilitate nuclear fusion via a different path as compared to early Universe Big Bang nucleosynthesis (BBN) or stellar core reactors?

V (process volume)

∞

km

cm

nm

BBN

Stars

ITER MegaJoule NIF

μCF

pB **plasmonics**

"Space plane" of fusion

fS   *μS minutes hours* ∞

Δt (process time)

BBN in a homogenous thermally equilibrated plasma which is dynamic and expands over time. Most stellar nucleosynthesis is an equilibrium process which is continuous and stable over large periods of time.
Some larger manmade fusion reactors are designed to operate for short pulsed periods of time.

Muon-catalyzed fusion (*μCF*) Proton-Boron fusion (*pB*)

Part II:
Short overview of natural fusion reactors

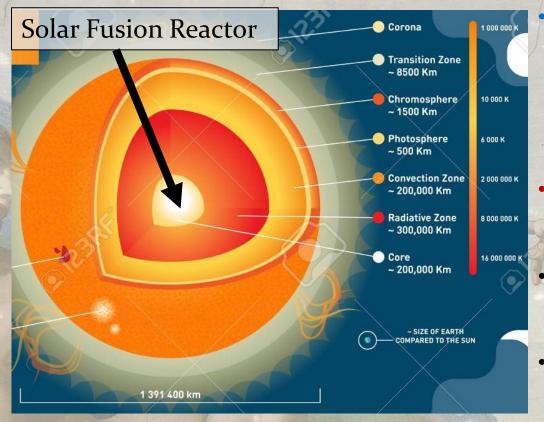Cauldrons in the Cosmos

NUCLEAR ASTROPHYSICS
Claus E. Rolfs and
William S. Rodney

Recommended introductory reading on nuclear processes in astronomy and cosmology. Published in 1988, so not entirely up to date.
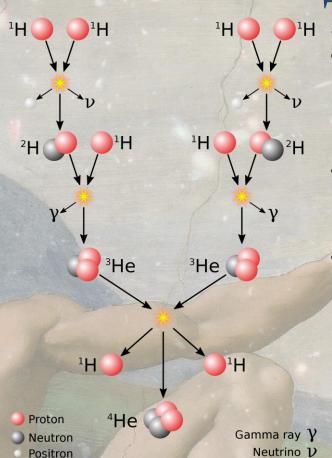
The fusion reactor powering the solar system

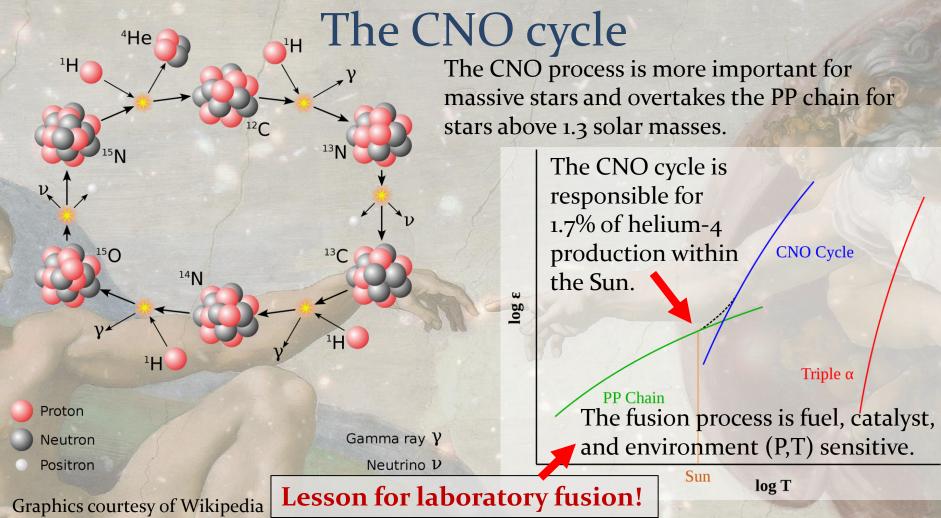**The sun is primarily made up of primordial hydrogen and helium.**

Solar Fusion Reactor

Corona — 1 000 000 K

Transition Zone ~ 8500 Km

Chromosphere ~ 1500 Km — 10 000 K

Photosphere ~ 500 Km — 6 000 K

Convection Zone ~ 200,000 Km — 2 000 000 K

Radiative Zone ~ 300,000 Km — 8 000 000 K

Core ~ 200,000 Km — 16 000 000 K

~ SIZE OF EARTH COMPARED TO THE SUN

1 391 400 km

- The Sun produces energy by converting hydrogen into helium-4. Two processes are well known:
  - Proton-Proton (PP) chain
  - Carbon-Nitrogen-Oxygen (CNO) cycle
- Gravity provides the confining force which balances the explosive radiative pressure.
- It produces 3.8×10^{26} W and has been continuously running for 4.6 billion years.
- The Earth is habitable by the grace of our "local" **stable** Solar core fusion nuclear reactor.

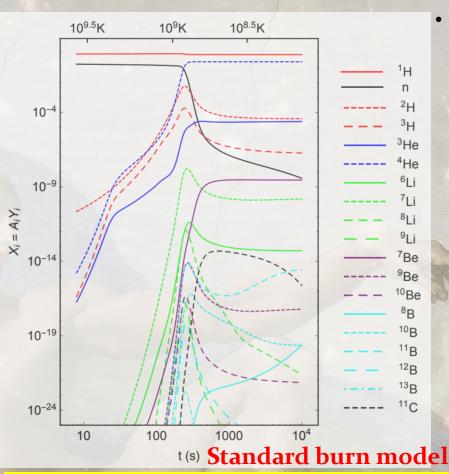# Primary power source of our Sun: The proton-proton chain

- This process is responsible for most of the energy production within the Sun as well as most low-mass stars.

- Every alpha produces releases about 14 MeV of energy from the binding energy per nucleon.

- The PP chain uses both the weak and strong interactions:
  - The weak interaction in the first step converts protons into deuterons.
  - The strong interaction then accomplishes the second and third steps to make intermediate helium-3 and finally the product helium-4.
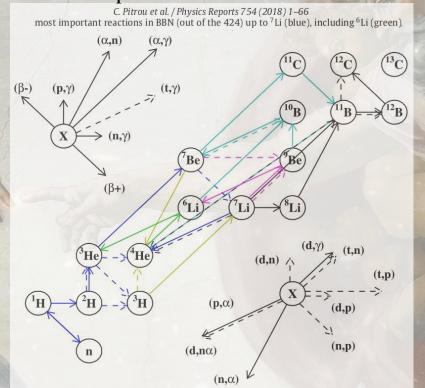
Proton
Neutron
Positron

Gamma ray γ
Neutrino ν

Graphic courtesy of Wikipedia

Secondary power source of our Sun: The CNO cycle

The CNO process is more important for massive stars and overtakes the PP chain for stars above 1.3 solar masses.

^{4}He
^{1}H
^{1}H
γ
^{12}C
^{15}N
^{13}N
ν
ν
^{15}O
^{13}C
^{14}N
γ
^{1}H
γ
^{1}H

Proton
Neutron
Positron

Gamma ray γ
Neutrino ν

The CNO cycle is responsible for 1.7% of helium-4 production within the Sun.

log ε
CNO Cycle
Triple α
PP Chain
Sun
log T

The fusion process is fuel, catalyst, and environment (P,T) sensitive.

Lesson for laboratory fusion!

Graphics courtesy of Wikipedia

The first nuclear burn in the universe: Big Bang nucleosynthesis
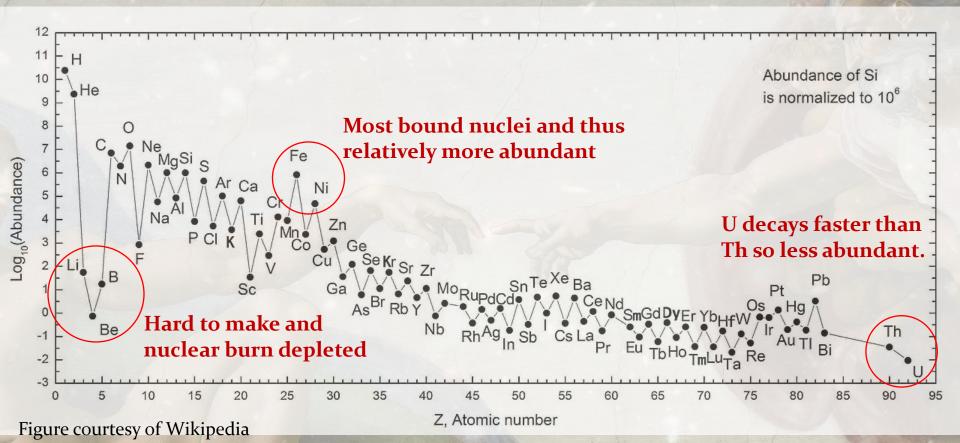
- BBN, unlike stellar burn, has neutrons available with a life-time of 880 seconds.
- BBN is responsible for the generation of the light elements in the early Universe while heavy elements are products of stellar evolution.

Standard burn model

C. Pitrou et al. / Physics Reports 754 (2018) 1–66
most important reactions in BBN (out of the 424) up to ^{7}Li (blue), including ^{6}Li (green)

C. Pitrou, et al. "Precision big bang nucleosynthesis with improved Helium-4 predictions." Physics Reports 754 (2018): 1-66.

The abundance of elements is the outcome of BBN and stellar nucleosynthesis

The light elements of lithium, boron and beryllium are suitable for aneutronic fusion.

Abundance of Si is normalized to 10^6

Most bound nuclei and thus relatively more abundant

U decays faster than Th so less abundant.

Hard to make and nuclear burn depleted

Figure courtesy of Wikipedia

Part III: Manmade fusion awakening

Dozens of government and commercial projects and companies are all chasing fusion.

Oct. 2007

$100 Billion

$100 Million

$10 Million

tae TECHNOLOGIES

Laser Mégajoule LMJ

HB11 ENERGY

NIF

Sandia National Laboratories

Z

Marvel Fusion

Nuclear pioneer First Light Fusion ignites plan for £400m fundraising

The Oxford-based nuclear fusion company is working with bankers at UBS to raise one of the biggest-ever funding rounds by a British energy start-up, Sky News learns.

Mark Kleinman
City editor @MarkKleinmanSky
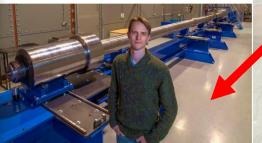
🕐 Tuesday 2 August 2022 12:28, UK

August 2022

Critical to this is the demonstration that its technology generates more energy than the amount expended in the process.

Dr Nick Hawker, chief executive of First Light Fusion with the UK's largest hyper-velocity gas gun

Kwasi Kwarteng, the business secretary, has said that the company's "British-born technology could potentially revolutionise power production in the coming decades".

First Light Fusion claims to have made more rapid progress towards its objectives than any other fusion technology in history.

Every month a new fusion startup pops up and asks for half a billion. The appetite is growing.

Governments are also recognizing modern fusion as a strategic investment opportunity.

ITER = International Thermonuclear Experimental Reactor

III-A: ITER is a $70 billion experiment: Start 2050?

CNN

Bottling the sun

The world has been trying to master this limitless clean energy source since the 1930s. We're now closer than ever

Story by Boštjan Videmšek
Photographs by Matjaž Krivic
May 30, 2022

ITER Divertor

ITER ORGANIZATION

ITER site in May 2021

scientific reports

www.nature.com/scientificreports

Potential design problems for ITER fusion device

A. Hassanein & V. Sizyuk

The ITER reactor design was simulated in full and exact 3D geometry including all known relevant physical processes involved during these transient events. The current ITER divertor design may not work properly and may requires significant modifications or new innovative design to prevent serious damage and to ensure successful operation.

Center for Materials Under Extreme Environment (CMUXE), Purdue University, West Lafayette, IN 47907, USA.
email: hassanein@purdue.edu

Scientific Reports | (2021) 11:2069 | https://doi.org/10.1038/s41598-021-81510-2   nature research   1

ISSUES & EVENTS   PHYSICS TODAY | MAY 2022

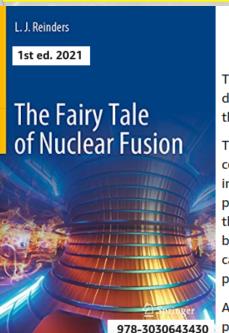# Further delays at ITER are certain, but their duration isn't clear

A halt to construction, pandemic-caused delays in deliveries, labor strife, and concerns about potential beryllium exposure are among recent challenges to the fusion project.

What others are saying about ITER

French Nobel laureate Pierre-Gilles de Gennes: "**The ITER project has been supported by Brussels for political image reasons and this is a mistake.**"

Another French Nobel laureate Georges Charpak: "**Let's stop ITER, the useless and overpriced reactor.**"

Claessens, M. (2020). Those Who Are Against ITER. In: ITER: The Giant Fusion Reactor. Copernicus, Cham. https://doi.org/10.1007/978-3-030-27581-5_7

ITER

L. J. Reinders

1st ed. 2021

The Fairy Tale of Nuclear Fusion

978-3030643430

The Fairy Tale of Nuclear Fusion
by L. J. Reinders ∨ (Author)

This carefully researched book presents facts and arguments showing, beyond a doubt, that nuclear fusion power will not be technically feasible in time to satisfy the world's urgent need for climate-neutral energy.

The author describes the 70-year history of nuclear fusion; the vain attempts to construct an energy-generating nuclear fusion power reactor, and shows that even in the most optimistic scenario nuclear fusion, in spite of the claims of its proponents, will not be able to make a sizable contribution to the energy mix in this century, whatever the outcome of ITER. This implies that fusion power will not be a factor in combating climate change, and that the race to save the climate with carbon-free energy will have been won or lost long before the first nuclear fusion power station comes on line.

Aimed at the general public as well as those whose decisions directly affect energy policy, this book will be a valuable resource for informing future debates.

L. J. Reinders

Sun in a Bottle? ... Pie in the Sky!

The Wishful Thinking of Nuclear Fusion Energy

Springer

978-3030747336

... unlike other areas of physics, investigations of fusion reactors became politicized relatively early. In the 1960s, independent research labs themselves decided what fusion research problems to pursue. But in the 1970s, the Atomic Energy Commission steered the fusion community away from fundamental research and toward the creation of commercial energy from fusion. It was just too soon to think about commercializing fusion because numerous fundamental issues in plasma physics had yet to be resolved. And in fact, that's still the case today...

Unsolved DT fusion problems

ORIGINAL RESEARCH

CrossMark

Fusion Neutrons: Tritium Breeding and Impact on Wall Materials and Components of Diagnostic Systems
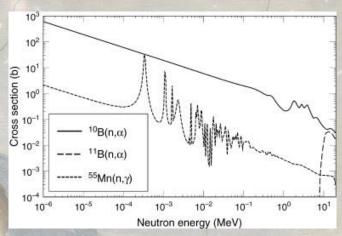
Marek Rubel[1]

The success or failure of DT based nuclear fusion resides in the reactor's ability to safely absorb the hard neutron radiation and self-produce its own fuel tritium.
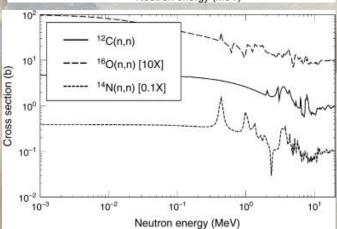
Fast neutrons are to deposit their energy in the absorber (reactor blanket) to facilitate heat exchange and transfer to electricity generating systems of a power plant and, simultaneously, for tritium production via nuclear reactions in the blanket.

The best way to exemplify the general power balance into consider a reactor of, for instance, 500 MW of fusion power. 80% of that (i.e. 400 MW) will be associated with neutrons and the rest (100 MW) with alphas. To the latter

• • •

steady–steady reactor operation. The entire dream and all hopes for commercial exploitation of controlled thermonuclear fusion for energy production depend on all aspects of power handling by PFC, efficient extraction of neutron energy and on efficient production, extraction and handling of tritium to fuel the reactor. In summary, it will depend on neutrons.

Where are we going to get all the tritium? (slide to follow)

Kovari M, et al. PROCESS: a systems code for fusion power plants—part 2: engineering, Fusion Eng Des 2016; 104:9–20.

DT fusion **safety** and **radioactive** waste

$= d$

$= t$

^1_1H $^2_1H = D$ $^3_1H = T$

α

β

γ

n

Intensity (arb. units) — E_n (MeV) — 5 keV — 10 keV

Fig. B.4. The DT neutron spectrum for ion temperatures of 5 keV and 10 keV showing the asymmetry of the spectrum with a greater intensity in the high-energy tail compared to the low-energy tail of the spectrum.

Paper   Aluminium   Lead   Thermal neutron absorber

14 MeV neutrons (dt process)

$v_n = 0.173c$

$$m_n c^2 = 940 \text{ MeV}$$

$$d + t \rightarrow \alpha(3.6 \text{ MeV}) + n(14 \text{ MeV})$$

DT fusion leads to super-fast neutrons and associated problems: My objective today is the development of aneutronic fusion in a dynamic regime i.e. non-thermal equilibrium, forbidden by brems-losses.

The trouble with dt-14 MeV neutrons
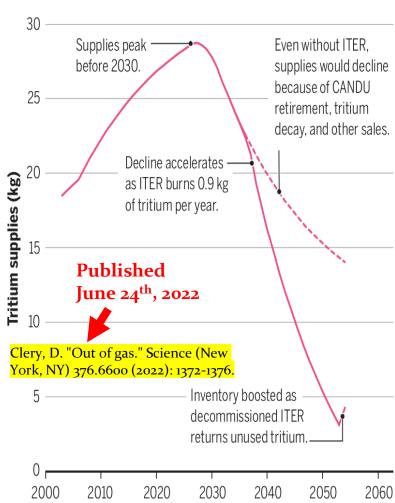
The collision cross-section of 14 MeV neutrons in matter is typically 10 times (or more!) smaller compared to MeV neutrons. Therefore, the neutron energy declines slowly from collisions (moderation). Containment walls must then be very thick. Much of the material is subject to element transmutation from exposure to such high energy and high intensity dt fusion neutrons.

Since 80% of fusion energy is released in the form of 14 MeV neutrons, the containment vessel is both the source of energy to drive the turbines and the source of tritium needed for fusion from element transmutation.

In aneutronic systems (e.g. pB), neutrons carry a fraction of a percent of the total energy and material for fusion can be mined.

The few kilograms of commercially available tritium come from CANDU plants, a type of nuclear reactor in Canada and South Korea. According to ITER projections, supplies will peak this decade, then begin a steady decline that will accelerate when ITER begins burning tritium.

Supplies peak before 2030.

Even without ITER, supplies would decline because of CANDU retirement, tritium decay, and other sales.

Decline accelerates as ITER burns 0.9 kg of tritium per year.

Published June 24th, 2022

Clery, D. "Out of gas." Science (New York, NY) 376.6600 (2022): 1372-1376.

Inventory boosted as decommissioned ITER returns unused tritium.

The trouble with tritium supply

One 1 GW electrical power reactor needs to produce about 2.8 GW of thermal power and burns 160 kg of tritium per year.

Is there enough tritium fuel to run just one reactor?

A dt-cycle fusion plant must produce tritium from the high flux of neutrons. The dt-fusion economy would need to be grown slowly into many reactors which is at risk from fuel disruption because of the natural decay of tritium.
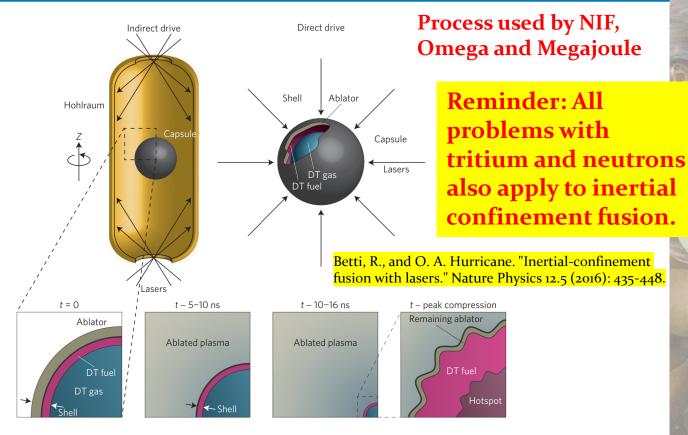
Breeding the excess amount of tritium required to grow the dt-fusion economy is an unsolved problem.

Conclusion: The dt-fusion economy, if technologically realizable, is well beyond a 100-year horizon. With technological advances in aneutronic fusion, the chance that the dt-fusion economy will be relevant is negligible.

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Part III-B: Inertial confinement fusion

REVIEW ARTICLES | INSIGHT

NATURE PHYSICS DOI: 10.1038/NPHYS3736

Process used by NIF, Omega and Megajoule

Reminder: All problems with tritium and neutrons also apply to inertial confinement fusion.

Betti, R., and O. A. Hurricane. "Inertial-confinement fusion with lasers." Nature Physics 12.5 (2016): 435-448.

Figure 1 | Schematics of indirect- and direct-drive ICF. Typical targets used in laser-driven ICF are indirectly driven (upper left) or directly driven (upper right). In either case, a spherical capsule is prepared at $t = 0$ with a layer of DT fuel on its inside surface. As the capsule surface absorbs energy and ablates, pressure accelerates the shell of remaining ablator and DT fuel inwards—an implosion. By the time the shell is at approximately one-fifth of its initial radius it is travelling at a speed of many hundreds of kilometres per second. By the time the implosion reaches minimum radius, a hotspot of DT has formed, surrounded by colder and denser DT fuel.

Unstable process which must be continuously repeated and yet is intrinsically difficult to repeat. This is a hard conundrum to solve.

Personal point of view: Direct drive inertial confinement laser fusion unsuitable for any meaningful power generation. It is useful for a femto-version of an H-bomb. This is also where the funding of NIF came from.

Inside the target chamber at the US National Ignition Facility.

LASER-FUSION FACILITY HEADS BACK TO THE DRAWING BOARD

Published July 22nd, 2022
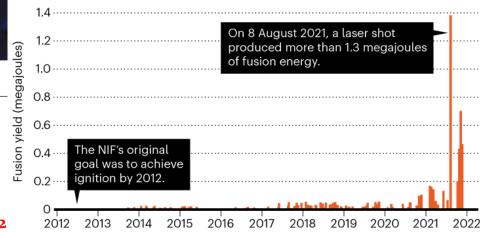
US scientists evaluate their options after failing to replicate record-setting experiment from 2021.

THE ROAD TO IGNITION

The National Ignition Facility (NIF) struggled for years before achieving a high-yield fusion reaction (considered ignition, by some measures) in 2021. Repeat experiments, however, produced less than half the energy of that result.

On 8 August 2021, a laser shot produced more than 1.3 megajoules of fusion energy.

The NIF's original goal was to achieve ignition by 2012.

©nature

Tollefson, Jeff. "Exclusive: Laser-fusion facility heads back to the drawing board." Nature 608.7921 (2022): 20-21.

Part III-C:
Muon-catalyzed fusion

J.D. Jackson reminisces in 2010: "**Luis Alvarez** and colleagues discovered muon-catalyzed fusion of hydrogen isotopes by chance in late 1956. On sabbatical leave at Princeton University during that year, I read the first public announcement of the discovery at the end of December in that well-known scientific journal, The New York Times. A nuclear theorist by prior training, I was intrigued enough in the phenomenon to begin some calculations."

Jackson, J.D. A Personal Adventure in Muon-Catalyzed Fusion. Phys. Perspect. 12, 74–88 (2010). https://doi.org/10.1007/s00016-009-0006-9

an Article from **SCIENTIFIC AMERICAN**   JULY, 1987   VOL. 255 NO. 7

$\mu-$ Cold Nuclear Fusion

The electronlike particles called muons can catalyze nuclear fusion reactions, eliminating the need for powerful lasers or high-temperature plasmas. The process may one day become a commercial energy source

by Johann Rafelski and Steven E. Jones
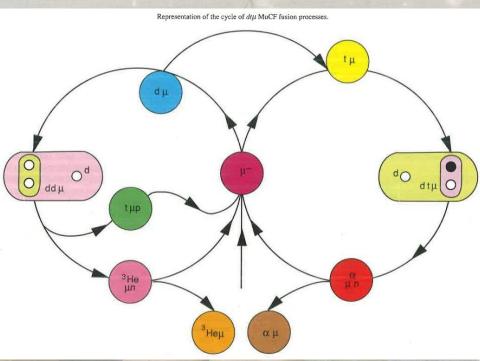
Different μCF hydrogen fusion processes

Here are all the muon-catalyzed fusion processes with hydrogen, but only the dt-fusion processes can be cycled many hundreds of times per muon.

MuCF hydrogen fusion reactions.

$$p + d \xrightarrow{(\mu)} \begin{cases} \sim .84\% & {}^3\text{He } (5.4 \text{ keV}) + \gamma \ (5.48 \text{ MeV}) \\ \sim 16\% & {}^3\text{He } (0.20 \text{ MeV}) + \mu \ (5.29 \text{ MeV}) \end{cases}$$

	S-wave	P-wave	
$d + d \xrightarrow{(\mu)}$	$\sim 52\%$	42%	$t \ (1.01 \text{ MeV}) + p \ (3.02 \text{ MeV})$
	$\sim 48\%$	58%	${}^3\text{He } (0.82 \text{ MeV}) + n \ (2.45 \text{ MeV})$

$$p + t \xrightarrow{(\mu)} {}^4\text{He } (52 \text{ keV}) + \gamma \ (19.76 \text{ MeV})$$

$$d + t \xrightarrow{(\mu)} {}^4\text{He } (3.56 \text{ MeV}) + n \ (14.03 \text{ MeV})$$

$$t + t \xrightarrow{(\mu)} {}^4\text{He} + n + n \ (11.33 \text{ MeV})$$

Muon-catalyzed fusion (μCF)

The muon is the catalyzer for dt-fusion allowing a single muon to facilitate many fusion events.

Representation of the cycle of $dt\mu$ MuCF fusion processes.

- The muon is a heavy electron with 207 times more mass therefore muonic atoms are shrunk by a factor of 207.
- Muonic molecules of hydrogen are then also shrunk which allows rapid spontaneous fusion at any temperature and pressure.
- For $dt\mu^+$ molecules, the fusion rate is a million times faster than the natural decay of the muon.
- The greatest challenge to μCF is the loss of the muon due to binding with the produced alpha particles. This limits the number of observed fusions to about 200 per muon.

The physics breakeven point for $dt\mu$ cycle was achieved around 1988.

Muon catalysed fusion

Q values (MeV) of the fusion reactions, reduced mass μ (MeV) of the nuclear system, $1s\sigma$ penetration constant $D_{1s\sigma}$, and an estimate of the reduced direct nuclear reaction rate $\tilde{\lambda}_f(s^{-1})$. 'Optimistic' and 'pessimistic' values of 0.5 and 1 were selected for ε, the optimistic values appearing in parentheses. Symmetry and quantum number selection rules have been disregarded.
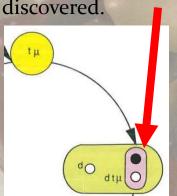
Reaction	Q	μ	$\log(D_{1s\sigma})$	$\log(\tilde{\lambda}_f)$	Reaction	Q	μ	$\log(D_{1s\sigma})$	$\log(\tilde{\lambda}_f)$
^{2}H + p	6	625	−5 (−3)	13 (15)	^{10}B + p	9	852	−6 (−6)	12 (13)
^{2}H + d	24	938	−6 (−4)	12 (14)	^{10}B + d	25	1562	−8 (−8)	10 (11)
					^{10}B + t	24	2159	−10 (−9)	8 (9)
^{3}H + p	20	703	−5 (−3)	12 (15)					
^{3}H + d	17	1125	−7 (−4)	11 (14)	^{11}B + p	16	860	−6 (−6)	12 (13)
^{3}H + t	12	1404	−8 (−5)	10 (13)	^{11}B + d	19	1586	−8 (−8)	10 (11)
					^{11}B + t	21	2205	−10 (−9)	8 (9)
^{3}He + d	17	1125	−7 (−5)	11 (13)					
^{3}He + t	16	1404	−7 (−6)	11 (12)	^{12}C + p	2	866	−6 (−6)	12 (13)
					^{12}C + d	10	1606	−9 (−8)	10 (10)
^{4}He + d	2	1248	−7 (−5)	11 (13)	^{12}C + t	15	2245	−10 (−9)	8 (9)
^{4}He + t	3	1602	−8 (−6)	10 (12)					
					^{13}C + p	8	871	−6 (−6)	12 (13)
^{6}Li + p	6	804	−6 (−5)	12 (13)	^{13}C + d	16	1624	−9 (−8)	10 (10)
^{6}Li + d	22	1405	−8 (−6)	10 (12)	^{13}C + t	13	2280	−10 (−10)	8 (9)
^{6}Li + t	18	1871	−9 (−8)	9 (11)					
					^{14}C + p	10	875	−6 (−6)	12 (13)
^{7}Li + p	17	820	−6 (−5)	12 (13)	^{14}C + d	11	1640	−9 (−8)	10 (10)
^{7}Li + d	17	1457	−8 (−7)	10 (12)	^{14}C + t	10	2311	−10 (−10)	8 (9)
^{7}Li + t	17	1964	−9 (−8)	9 (10)					
					^{14}N + p	7	875	−6 (−6)	12 (13)
^{9}Be + p		844	−6 (−5)	12 (13)	^{14}N + d	21	1640	−9 (−8)	10 (10)
^{9}Be + d	16	1533	−8 (−7)	10 (11)	^{14}N + t	19	2311	−11 (−10)	8 (8)
^{10}Be + t	13	2105	−10 (−9)	8 (10)					
					^{15}N + p	12	879	−6 (−6)	12 (13)
^{10}Be + p	11	853	−6 (−5)	12 (13)	^{15}N + d	14	1654	−9 (−8)	10 (10)
^{10}Be + d	13	1562	−8 (−7)	10 (11)	^{15}N + t	16	2339	−11 (−10)	8 (8)
^{10}Be + t	11	2159	−10 (−9)	8 (9)					

Search for aneutronic μCF
All possible light element fusion reactions

Much work can still be done in this field!
Resonant mesomolecular processes would need to be discovered.

Part III-D:
Laser driven aneutronic proton-boron fusion

Belyaev, V.S.; et al. (2005). "Observation of neutronless fusion reactions in picosecond laser plasmas". Physical Review E. 72 (2): 026406. doi:10.1103/physreve.72.026406

news@nature.com
The best in science journalism

Published online: 26 August 2005; | doi:10.1038/news050822-10

Lasers trigger cleaner fusion

Neutron-free reaction makes less radioactive waste.

Mark Peplow

Two-laser process

Aneutronic fusion reactions require a spark of protons in the 0.01-1 MeV energy range

Patent

Production of energy via laser-initiated aneutronic nuclear fusion reactions

Abstract

The invention relates to the production of energy with laser beams, involving: a) exciting a fuel target (4) into a plasma state using a first set of laser beams (1); b) bombarding the fuel target in the plasma state with particles generated using a second set of laser beams (2), the fuel and the particles being chosen so that the interaction between the fuel target in the plasma state and the particles produce non-thermal equilibrium aneutronic nuclear reactions; and c) recovering energy from the ions generated by the aneutronic nuclear reactions.

WO2013144482A1
WIPO (PCT)

2013-10-03 · Publication of WO2013144482A1

Other languages: French
Application PCT/FR2013/050558
2012-03-27 · Priority to FR1252750A
Inventor: Christine LABAUNE, Johann Rafelski, Sylvie DEPIERREUX, Clément GOYON, Vincent YAHIA

A mJ femtosecond laser is capable of producing reactant protons for fusion

For any aneutronic fusion process, cheap and abundant MeV scale protons are essential.

Dan Levy,[1, *] Igor A. Andriyash,[2, †] Stefan Haessler,[2, ‡] Jaismeen Kaur,[2] Marie Ouillé,[2, 3] Alessandro Flacco,[2] Eyal Kroupp,[1] Victor Malka,[1] and Rodrigo Lopez-Martens[2]

[1] Department of Physics of Complex Systems, Weizmann Institute of Science, Rehovot 76100, Israel
[2] Laboratoire d'Optique Appliquée, ENSTA Paris, CNRS, Ecole Polytechnique, Institut Polytechnique de Paris, 828 Bd des Maréchaux, 91762 Palaiseau, France
[3] Ardop Engineering, Cité de la Photonique, 11 Avenue de la Canteranne, Bât. Pléione, 33600 Pessac, France

Proton beams with up to 100 pC bunch charge, 0.48 MeV cut-off energy and divergence as low as a 3° were generated from solid targets at kHz repetition rate by a few-mJ femtosecond laser under controlled plasma conditions. The beam spatial profile was measured using a small aperture scanning time-of-flight detector. Detailed parametric studies were performed by varying the surface plasma scale length from 8 to 80 nm and the laser pulse duration from 4 fs to 1.5 ps. Numerical simulations are in good agreement with observations and, together with an in-depth theoretical analysis of the acceleration mechanism, indicate that high repetition rate femtosecond laser technology could be used to produce few-MeV protons beams for applications.

arXiv:2112.12581 16 Dec 2021 (v1), last revised 12 Jul 2022
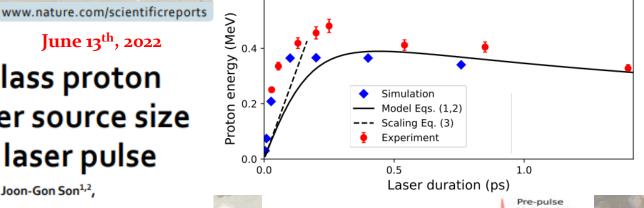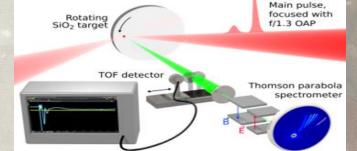
June 13th, 2022

Low divergent MeV-class proton beam with micrometer source size driven by a few-cycle laser pulse

Prashant K. Singh[1✉], Parvin Varmazyar[1], Bence Nagy[1], Joon-Gon Son[1,2], Sargis Ter-Avetisyan[1] & Karoly Osvay[1,3✉]

Spatial characterization of 0.5 MeV proton beam, driven by 12 fs, 35 mJ, 10^{19} W/cm² intense laser-foil interaction is presented. The accelerated proton beam has been applied to obtain a high-resolution, point-projection static radiograph of a fine mesh using a CR-39 plate. The reconstruction of mesh edge blurring and particle ray tracing suggests that these protons have an effective source size (FWHM) of just 3.3 ± 0.3 μm. Furthermore, the spatial distribution of the proton beam recorded on the CR-39 showed that the divergence of these particles is less than 5-degree (FWHM). The low divergence and small source size of the proton beam resulted in an ultralow transverse emittance of 0.00032 π-mm-mrad, which is several orders of magnitude smaller than that of a conventional accelerator beam.

Two-laser pB process

The long-pulsed nano-laser produces plasma and sweeps electrons away.

The short-pulsed pico-laser produces a beam of reactant protons. Fusion reactions occur prior to protons reaching thermal equilibrium.
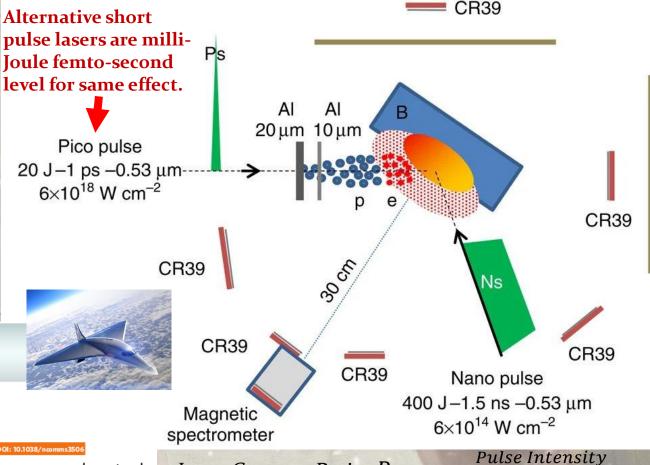
nature COMMUNICATIONS

Fusion reactions initiated by laser-accelerated particle beams in a laser-produced plasma

C. Labaune[1], C. Baccou[1], S. Depierreux[2], C. Goyon[2], G. Loisel[1], V. Yahia[1] & J. Rafelski[3]

Fusion reactions initiated by laser-accelerated particle beams in a laser-produced plasma

Scheme of the experimental set-up showing the laser beam configuration, the target arrangement and the diagnostics

Alternative short pulse lasers are milli-Joule femto-second level for same effect.

CR39

Ps

Pico pulse
20 J −1 ps −0.53 μm
6×10^{18} W cm^{-2}

Al 20 μm   Al 10 μm   B

p   e

CR39

CR39

30 cm

Ns

CR39

CR39

CR39

Magnetic spectrometer

Nano pulse
400 J −1.5 ns −0.53 μm
6×10^{14} W cm^{-2}
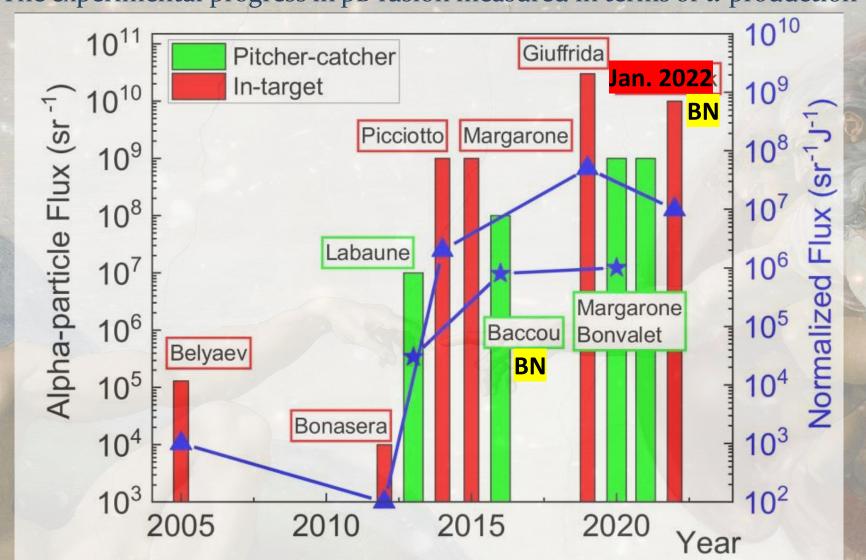
Laser Contrast Ratio: $R = \dfrac{Pulse\ Intensity}{Prepulse/pedestal\ Intenity}$

The laser contrast ratio is a crucial parameter in achieving laser-driven nuclear fusion.

The experimental progress in pB fusion measured in terms of α production

Why boron-nitride?
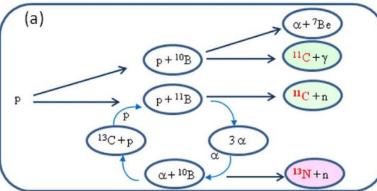
1. Chain of sustained reactions: Micro-explosions.
2. Boron-nitrides forms Buckyball nanostructures akin to C_{60}
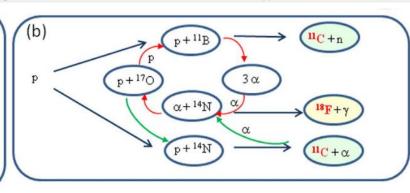3. Change of fuel, but otherwise same two-laser process.

Laser-initiated primary and secondary nuclear reactions in Boron-Nitride

C. Labaune[1], C. Baccou[1], V. Yahia[1], C. Neuville[1] & J. Rafelski[2]

Nuclear reactions initiated by laser-accelerated particle beams are a promising new approach to many applications, from medical radioisotopes to aneutronic energy production. We present results demonstrating the occurrence of secondary nuclear reactions, initiated by the primary nuclear reaction products, using multicomponent targets composed of either natural boron (B) or natural boron nitride (BN). The primary proton-boron reaction ($p + {}^{11}B \rightarrow 3\alpha + 8.7\,MeV$), is one of the most attractive aneutronic fusion reaction. We report radioactive decay signatures in targets irradiated at the Elfie laser facility by laser-accelerated particle beams which we interpret as due to secondary reactions induced by alpha (α) particles produced in the primary reactions. Use of a second nanosecond laser beam, adequately synchronized with the short laser pulse to produce a plasma target, further enhanced the reaction rates. High rates and chains of reactions are essential for most applications.

Scheme of the primary and secondary nuclear reactions produced by the interaction between a laser-accelerated proton beam and (**a**) a natural boron target, (**b**) a boron-nitride target. In the case of the BN targets the reactions with ^{10}B can also occur but are not shown for clarity.

Part III-E:
Plasmonic fusion

Antennas for light

nature photonics — REVIEW ARTICLE
PUBLISHED ONLINE: 1 FEBRUARY 2011 | DOI: 10.1038/NPHOTON.2010.237

Lukas Novotny[1*] and Niek van Hulst[2,3]

Optical antennas are devices that convert freely propagating optical radiation into localized energy, and vice versa. They enable the control and manipulation of optical fields at the nanometre scale, and hold promise for enhancing the performance and efficiency of photodetection, light emission and sensing. Although many of the properties and parameters of optical antennas are similar to their radiowave and microwave counterparts, they have important differences resulting from their small size and the resonant properties of metal nanostructures. This Review summarizes the physical properties of optical antennas, provides a summary of some of the most important recent developments in the field, discusses the potential applications and identifies the future challenges and opportunities.

PHYSICAL REVIEW LETTERS

66802 (2007)

Effective Wavelength Scaling for Optical Antennas

Lukas Novotny*

Institute of Optics, University of Rochester, Rochester, New York, USA
(Received 27 March 2007; published 27 June 2007)

In antenna theory, antenna parameters are directly related to the wavelength λ of incident radiation, but this scaling fails at optical frequencies where metals behave as strongly coupled plasmas. In this Letter we show that antenna designs can be transferred to the *optical* frequency regime by replacing λ by a linearly scaled effective wavelength $\lambda_{eff} = n_1 + n_2 \lambda / \lambda_p$, with λ_p being the plasma wavelength and n_1, n_2 being coefficients that depend on geometry and material properties. It is assumed that the antenna is made of linear segments with radii $R \ll \lambda$. Optical antennas hold great promise for increasing the efficiency of photovoltaics, light-emitting devices, and optical sensors.

PRX ENERGY

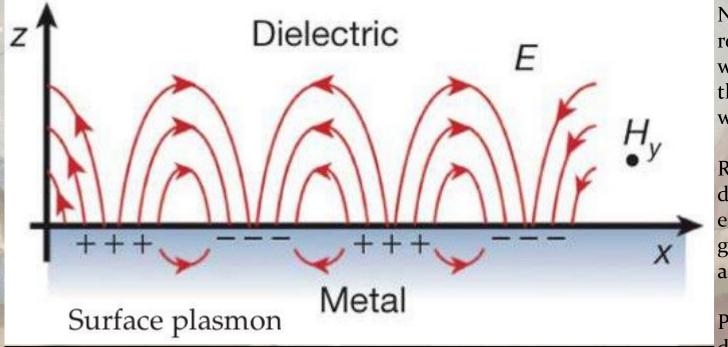### Kinetic Model Evaluation of the Resilience of Plasmonic Nanoantennas for Laser-Induced Fusion

István Papp, Larissa Bravina, Mária Csete, Archana Kumari, Igor N. Mishustin, Dénes Molnár, Anton Motornenko, Péter Rácz, Leonid M. Satarov, Horst Stöcker, Daniel D. Strottman, András Szenes, Dávid Vass, Tamás S. Biró, László P. Csernai, and Norbert Kroó (NAPLIFE Collaboration)

Recently, a new version of laser-induced fusion was proposed where implanted nanoantennas regulated and amplified the light absorption in the fusion target [L.P. Csernai *et al.*, Phys. Wave Phenom. 28, 187–99 (2020)]. In this paper we estimate the nanoantenna lifetime in a dynamical kinetic model and describe how electrons are leaving the nanoantenna's surface, and for how long the plasmonic effect is maintained. Our model successfully shows a nanorod antenna lifetime that will allow future fusion studies with top-energy short laser ignition pulses.

Surface electro-magnetic fields
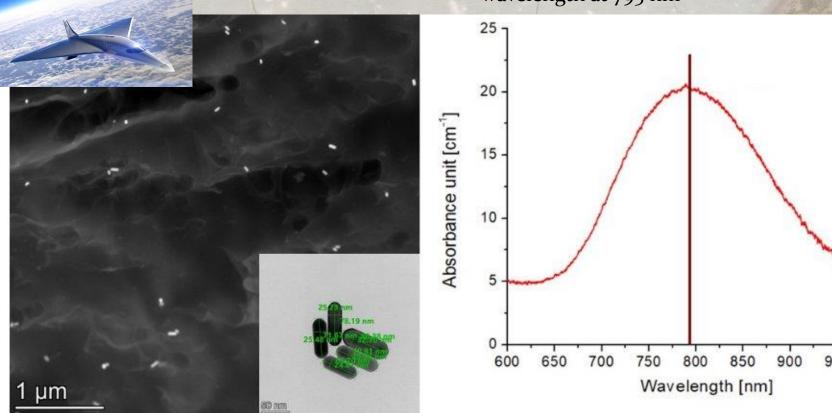# 1000-fold (in numerical model) amplified

Nanoparticles act as resonant antennas working at a fraction of the incident light's wavelength.

Resonance wavelength is determined by the electron density and geometry of the antenna.

Plasmon coherent dynamics lifespan requires sub-picosecond laser pulses.

Commercially available femto-sec mJ lasers can excite surface plasmons in dielectrics which can accelerate protons to MeV energies.

The NAPlife plasmonic fusion project

UDMA polymer with resonant gold nano-rods

Gold nano-rods embedded in polymer matrix: Transmission electron microscope image; insert shows actual nano-rods

Actual absorption curve for nano composites measured by optical spectroscopy. The absorption peak is tuned to resonate with laser wavelength at 795 nm
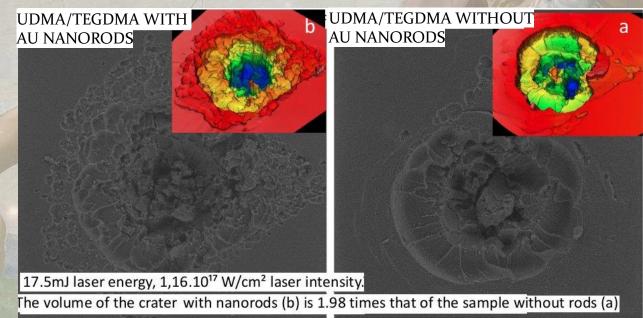
The NAPlife plasmonic fusion project
Three diagnostic methods for nuclear reactions

1. In prior laser fusion experiments detection of **helium production** played a pivotal role. This will be accomplished by the (laser-induced breakdown spectroscopy) LIBS study of plasma plumes emerging from the crater drilled by a laser shot into the polymer target. This can be supported by a mass spectrometry measurement of the plume compounds. Information about the alpha energy spectrum can be obtained from analysis of CR39 passive detectors.

2. The study of **deuterium content** is addressed by Raman scattering on the reaction crater surface.

3. The novel **energy production** measurement is achieved in the study of crater morphology: any energy production comparable in magnitude to the laser shot energy will be measured in terms of the quantity of material ejected. As a reminder, one Joule of energy corresponds to approximately 10^{12} fusion reactions. Polymer micro-structure damage relates to fusion product impacts, compare pB fusion CR39 detectors.

UDMA/TEGDMA WITH AU NANORODS

UDMA/TEGDMA WITHOUT AU NANORODS

17.5mJ laser energy, $1,16.10^{17}$ W/cm² laser intensity.
The volume of the crater with nanorods (b) is 1.98 times that of the sample without rods (a)

SEM HV: 8.0 kV	Det: BSE		MIRA3 TESCAN
SM: RESOLUTION	Stage Tilt: 0.0°	50 µm	
SEM MAG: 6.40 kx	Date(m/d/y): 02/16/22	Wigner Research Centre for Physics	

SEM HV: 8.0 kV	Det: BSE		MIRA3 TESCAN
SM: RESOLUTION	Stage Tilt: 0.0°	50 µm	
SEM MAG: 6.40 kx	Date(m/d/y): 02/23/22	Wigner Research Centre for Physics	

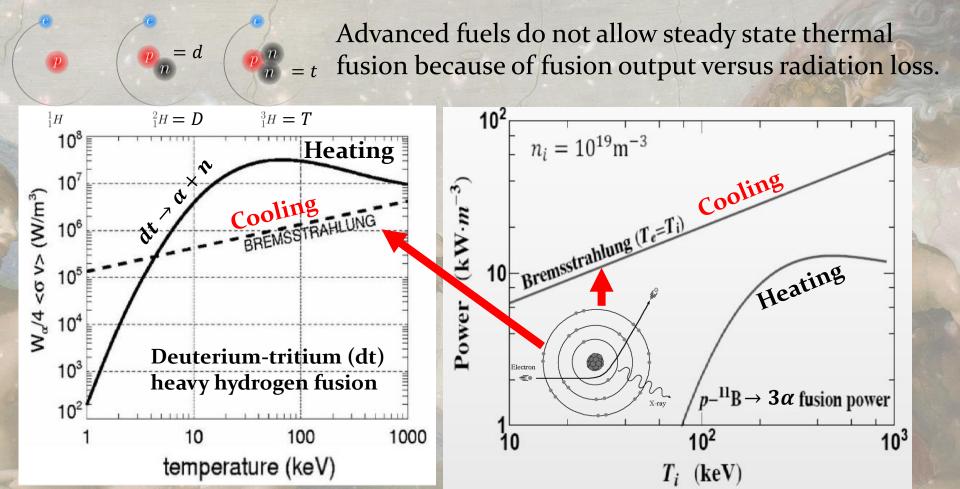Tamás Biró   László Pál Csernai   Norbert Kroó

NAPlife Collaboration:
Márk Aladi, Tamás S Biró, Attila Bonyár, Alexandra Borók, László P Csernai, Mária Csete, Attila Czirják, Péter Dombi, Olivér Fekete, Péter Földi, Gábor Galbács, Román Holomb, Csaba Horváth, Judit Kámán, Miklós Kedves, Norbert Kroó, Archana Kumari, Ágnes N Szokol, István Papp, Péter Petrik, Béla Ráczkevi, Péter Rácz, István Rigó, Melinda Szalóki, András Szenes, Ádám Takács, Csaba Tóth, Emese Tóth, Dávid Vass, Miklós Veres, Shereen Zangna

Part IV: Key Insights
Comparing neutronic and aneutronic fusion
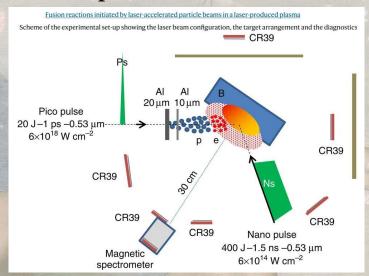
Advanced fuels do not allow steady state thermal fusion because of fusion output versus radiation loss.

Comparing traditional thermal fusion from modern nuclear fusion approaches
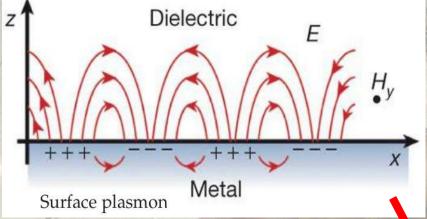
> **Modern nuclear fusion processes occur under inequilibrium conditions with the objective to spark a nano-fusion explosion which is short lived.**

pB nuclear fusion

Fusion reactions initiated by laser-accelerated particle beams in a laser-produced plasma

Scheme of the experimental set-up showing the laser beam configuration, the target arrangement and the diagnostics

Plasmonic nuclear fusion

The long-pulsed nano-laser produces plasma and sweeps electrons away. The short-pulsed pico-laser produces a beam of reactant protons. Fusion reactions occur prior to protons reaching thermal equilibrium.

The nano-sized antenna are "energized" to an extreme degree by the incident laser and in the brief moment before the antenna is destroyed, the surface plasmons accelerate particles to required fusion conditions.

Comparing modern approaches

How close are we to "space plane" fusion in both the figurative and literal sense? How will we power the real future space planes that can travel across the solar system?

4,000 years

100 years

LASER RADIATION

Recap:
- μCF opened the door to considering fusion processes outside the thermal regime
- pB laser driven fusion remains an essential technological exploration towards table-top fusion
- Plasmonic fusion satisfies all the requirements of truly table-top fusion:
    - Femto-attosecond high contrast laser pulse
    - Aneutronic
    - Different nuclear fuels can be attempted
    - Today exploring processes with scalable commercial laser technology
    - Transferable to **ELI-Alps** laser for large scale energy production

Summary

- Early successes with muon catalyzed fusion clouded by use of weapon grade dt-cycle.

- Non-equilibrium short pulse laser driven environments have been recognized as the key ingredient allowing realization of nuclear fusion energy production

- Even milli-Joule pulses with near/sub femto-second pulse lengths with an extremely high contrast laser pulse profile (pulse length at wavelength scale) should create required fusion conditions in the context of nano-rod amplified targets.
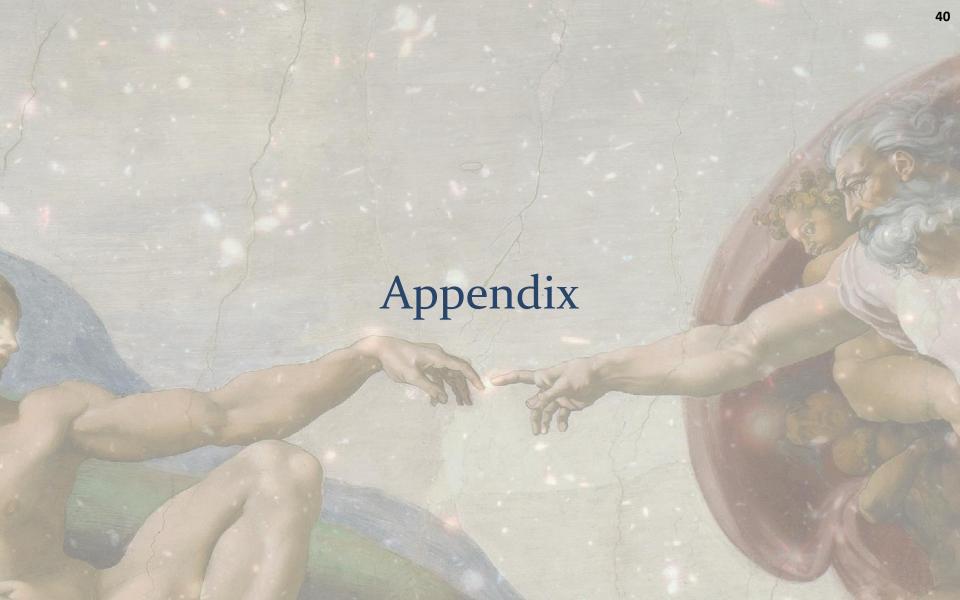
Future Research

a) study of laser pulse EM interaction with nano-antennas: Domain of strong field physics

b) development of multiple component aneutronic chain fusion: Domain of nuclear physics

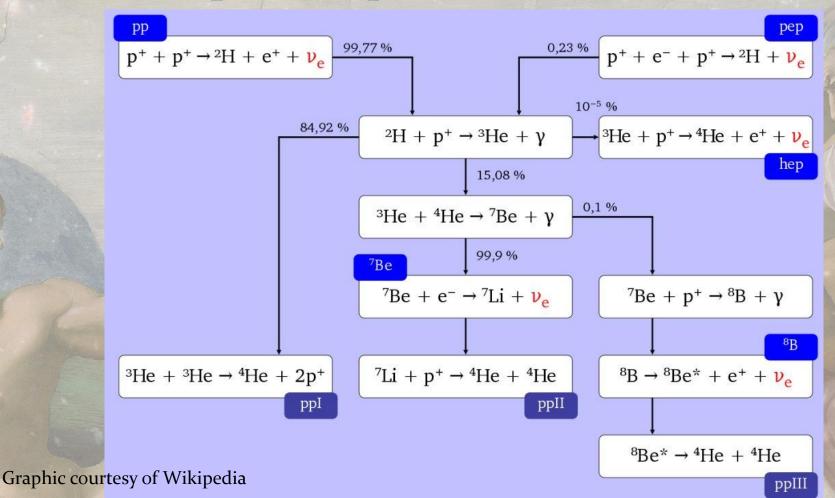c) development of ignition nano-target geometry: Domain of numerical modeling / applied math

Thank you for your attention!

Johann Rafelski

Appendix

The proton-proton chain in detail

$$pp \quad p^+ + p^+ \rightarrow {}^2H + e^+ + \nu_e$$

$$99,77\,\%$$

$$pep \quad p^+ + e^- + p^+ \rightarrow {}^2H + \nu_e$$

$$0,23\,\%$$

$$10^{-5}\,\%$$

$$84,92\,\% \quad {}^2H + p^+ \rightarrow {}^3He + \gamma \quad \rightarrow \quad {}^3He + p^+ \rightarrow {}^4He + e^+ + \nu_e$$

$$hep$$

$$15,08\,\%$$

$${}^3He + {}^4He \rightarrow {}^7Be + \gamma \quad 0,1\,\%$$

$$99,9\,\%$$

$${}^7Be \quad {}^7Be + e^- \rightarrow {}^7Li + \nu_e \quad {}^7Be + p^+ \rightarrow {}^8B + \gamma$$

$${}^8B$$

$${}^3He + {}^3He \rightarrow {}^4He + 2p^+ \quad {}^7Li + p^+ \rightarrow {}^4He + {}^4He \quad {}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$$

$$ppI \quad ppII$$

$${}^8Be^* \rightarrow {}^4He + {}^4He$$

$$ppIII$$

Graphic courtesy of Wikipedia

Part III: Manmade fusion awakening

- III-A: ITER: International Thermonuclear Experimental "Reactor" (Since Oct 2007 in France: China, EU+, India, Japan, S Korea, Russia, USA)
  ITER is a steady state device.
- III-B: Inertial-confinement fusion:
  i.   with lasers (NIF, Omega)   ii.   with heavy ions (GSI) **inactive**

France=MegaJoule; seeks to ignite a small drop containing dt by a high-powered laser beam assembly. This is an imitation of nuclear H-bomb explosions.

Processes outside the thermal regime:

- III-C: Muon Catalyzed Fusion

J.D. Jackson reminisces: **Luis Alvarez** and colleagues discovered muon-catalyzed fusion of hydrogen isotopes by chance in late 1956. On sabbatical leave at Princeton University during that year, I read the first public announcement of the discovery at the end of December in that well-known scientific journal, The New York Times. A nuclear theorist by prior training, I was intrigued enough in the phenomenon to begin some calculations.

Jackson, J.D. A Personal Adventure in Muon-Catalyzed Fusion. Phys. Perspect. 12, 74–88 (2010). https://doi.org/10.1007/s00016-009-0006-9

- III-D: Pulsed laser aneutronic pB fusion

Belyaev, V.S.; et al. (2005). "Observation of neutronless fusion reactions in picosecond laser plasmas". Physical Review E. 72 (2): 026406. doi:10.1103/physreve.72.026406

- III-E: Plasmonic fusion (with pulsed lasers)

Begins in 2021: NAPlife project. Concentrations of light energy with nanorods: Antennas for light!

The awakening of fusion opportunities

Readout of the White House Summit on Developing a Bold Decadal Vision for Commercial Fusion Energy

APRIL 19, 2022 • PRESS RELEASES

THE RACE TO FUSION ENERGY

An emerging industry of nuclear fusion firms promises commercial reactors in the next decade. **By Philip Ball**

The ancient village of Culham, nestled in a bend of the River Thames west of London, seems an unlikely launching pad for the future. But next year, construction will start here on a gleaming building of glass and steel that could house what many people consider to be an essential technology to meet demand for clean energy in the twenty-first century and beyond.

Long derided as a prospect that is forever 30 years away, nuclear fusion seems finally to be approaching commercial viability. There are now more than 30 private fusion firms globally, according to an October survey by the Fusion Industry Association (FIA) in Washington DC, which represents companies in the sector; the 18 firms that have declared their funding say they have attracted more than US$2.4 billion in total, almost entirely from private investments. Key to these efforts are

362 | Nature | Vol 599 | 18 November 2021

The tantalizing promise is marred by hidden pitfalls

The most famous example of a pitfall is the "cold fusion" of 1989 which has been currently rebranded as "Low-Energy Nuclear Reactions" or LENR.
Perfect topic for TV shows (Dr. Who) and movies (The Saint) which I enjoy. Airbus and Google should take note.

Airbus Files Patent for LENR 'Power-Generating Device'

Posted on March 22, 2015 • 102 Comments

Thanks to AlainCo for posting about a recently published patent application submitted by European Aerospace giant Airbus for an 'apparatus and method for power generation'. It appears that patent was first submitted on September 17, 2013, and was made public on March 19th, 2015. So it seems that Airbus has been paying attention for quite some time now, perhaps they were inspired by the publication of the E-Cat report by Levi et al which was published in May 2013.

NEWS | 27 May 2019 | Clarification 28 May 2019

Google revives controversial cold-fusion experiments

Researchers tested mechanisms linked to nuclear fusion at room temperature — but found no evidence for the phenomenon.
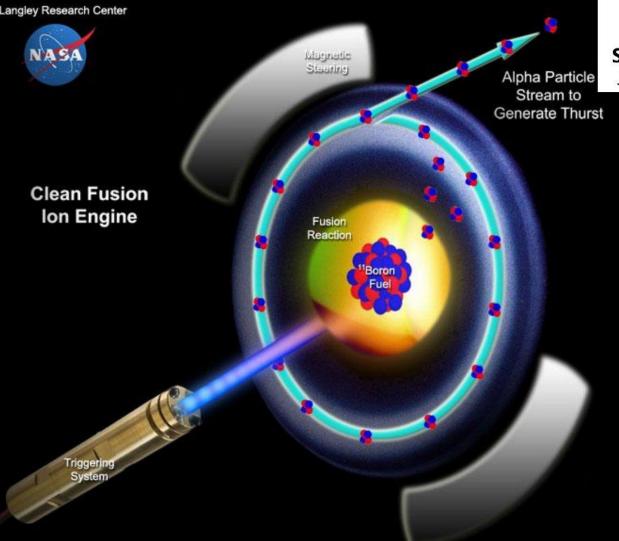
Langley Research Center

NASA

Clean Fusion Ion Engine

Magnetic Steering

Alpha Particle Stream to Generate Thurst

Fusion Reaction

11Boron Fuel

Triggering System

Advanced Fusion Reactors for Space Propulsion and Power Systems
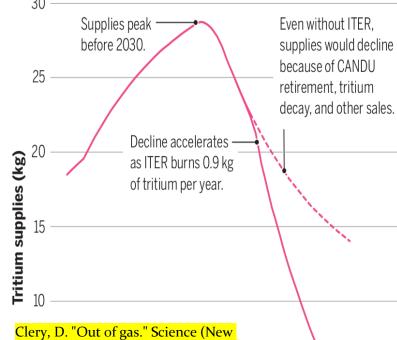
John J. Chapman, NASA, Langley Research Center

2011

Advanced clean fusion ion engine system uses scientifically proven concepts to offer a unique solution to space applications. Abundantly available, Boron-11 fuel undergoes transmutation via a pulsed p-B11 plasma process to produce thrust in a novel & efficient fashion. Nuclear gain enables a dramatic performance increase as compared to existing ionic propulsion and power technology. Efficiency improvements are due to delivery of high velocity ions from plasma to exhaust while eliminating the customary radioactive isotopes as fuel stocks and reaction by-products

The few kilograms of commercially available tritium come from CANDU plants, a type of nuclear reactor in Canada and South Korea. According to ITER projections, supplies will peak this decade, then begin a steady decline that will accelerate when ITER begins burning tritium.

Supplies peak before 2030.

Even without ITER, supplies would decline because of CANDU retirement, tritium decay, and other sales.

Decline accelerates as ITER burns 0.9 kg of tritium per year.

Inventory boosted as decommissioned ITER returns unused tritium.

Clery, D. "Out of gas." Science (New York, NY) 376.6600 (2022): 1372-1376.

The trouble with tritium supply

$$A = \frac{C}{s} = 6.24 \times 10^{18} \frac{\text{electrons}}{\text{second}}$$

$$W = VA = 6.24 \times 10^{18} \text{ eV/s}$$

$$\text{\# of fusions to produce 1 W} = \frac{6.24 \times 10^{18} \frac{\text{eV}}{\text{s}}}{17.6 \text{ MeV}}$$

$$\boxed{1 \text{ W} \;\widehat{=}\; 3.55 \times 10^{11} \frac{\textbf{dt fusions}}{\textbf{second}}}$$

One 1 GW electrical power reactor needs to produce about 2.8 GW thermal power and this requires 10^{21} dt-fusions per second. Per year this amounts to
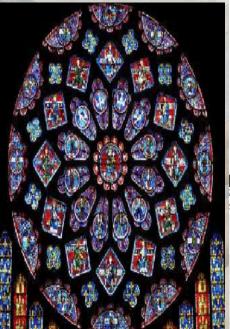
$$\text{\# of fusion to run a reactor for 1 year} = 3.15 \times 10^{28}$$

which is **160 kg of tritium per year**.

$$6.02 \times 10^{23} \text{ tritons} \;\widehat{=}\; 3 \text{ grams}$$

Plasmonics: A vibrant & ancient research field

A nano-sized piece of metal can be viewed as a box trapping free electron plasma. The domain of physics describing how light interacts with metallic nano-structures embedded in an insulator is called **plasmonics.** Extreme daily light absorption properties of metallic nano particles have been empirically recognized and used in **medieval stained glass** (see e.g. The Grande Rose of the Chartres Cathedral); and in precious objects made of glass during the **Roman era (e.g. Lycurgus drinking cup).**

The Lycurgus Cup
A Roman
Nanotechnology

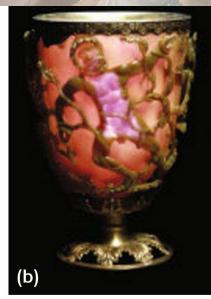Ian Freestone[1], Nigel Meeks[2],
Margaret Sax[2] and Catherine Higgitt[2]

Transmission electron microscopy (TEM) image of a silver-gold alloy particle within the glass of the Lycurgus Cup

50 nm

(a)

(b)

The Lycurgus Cup *1958,1202.1 in reflected (a) and transmitted (b) light. Scene showing Lycurgus being enmeshed by Ambrosia*

Technological applications of plasmonics phenomenon

Owing to their unique laser light energy concentration properties nano particles are considered for:
1) Thermal treatment of cancer;
2) As enhancers of solar cell efficiency;
3) They are studied at the NAPlife research program in Hungary for their capability to enhance and stimulate laser induced nuclear fusion.
4) And many more…

Near-infrared laser beam

Tumor

Excited nanoshells

Healthy tissue

Gold

Silica

A proposed cancer treatment would employ plasmonic effects to destroy tumors. Doctors would inject nanoshells—100-nanometer-wide silica particles with an outer layer of gold (inset)—into the bloodstream. The nanoshells would embed themselves in a fast-growing tumor. If near-infrared laser light is pointed at the area, it would travel through the skin and induce resonant electron oscillations in the nanoshells, heating and killing tumor cells without harming the surrounding healthy tissue.

Plasmonic nanorods are embedded in a laser-light transparent resin

The media is initially a fluid monomer but is converted to a rigid polymer through polymerization. The most commonly used monomers for dental composites are bis-GMA and *UDMA*, which are diluted by a viscosity controller such as MMA, EGDMA or *TEGDMA* (most commonly used). Polymerization of dental composites may be achieved by chemical means (self-curing) or by external energy activation (heat or light).

bisphenol A-glycidyl methacrylate — bis-GMA

urethane dimethacrylate — UDMA

triethylene glycol dimethacrylate — TEGDMA

2-hydroxyethyl methacrylate — HEMA

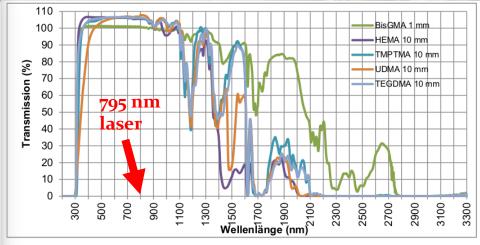1,6-hexanediol dimethacrylate — HDDMA

795 nm laser

Abb. 36: **Transmissionsspektrum der Monomere BisGMA, HEMA, TMPTMA, UDMA und TEGDMA** **(Mittelwerte)** im Rahmen der spektroskopischen Untersuchung von Füllungs- und Befestigungswerkstoffen am Institut für Lasertechnologien in der Medizin und Messtechnik an der Universität Ulm von 2013 bis 2016. Die Probendicken sind rechts oben in der Legende genannt. (Abkürzungen: % = Prozent; nm = Nanometer; BisGMA = Bisphenol-A-glycidyl-methacrylat; HEMA = Hydroxymethylmethacrylat; TMPTMA = Trimethylpropan-Trimethacrylat; UDMA = Urethan-dimethacrylat; TEGDMA = Triethylenglycol-dimethacrylat; mm = Millimeter)

What is this talk about?

- The different nuclear fusion processes in nature
- Pros and con of man-made nuclear fusion
- Explanation of principles and ideas in fusion processes
- The search and economic interest in fusion
- The windy path to novel realizations of fusion
- The future of nuclear fusion energy (pB, plasmonics, …)

What is this talk <u>not</u> about?

- Not an introduction to nuclear reaction theory
- Not an introduction to high-intensity short-pulsed laser physics
- Not an introduction to plasmonic physics mechanisms
- Not a sales pitch