This talk is evolved from a Hungarian Academy of Science inaugural presentation on June 13th, 2022.
Searching for Viable Paths to Nuclear Fusion Energy

Presented at the XI International Conference on New Frontiers in Physics
September 8th, 2022

Johann Rafelski

Budapest; Photo by László Pál Csernai
Abstract

Nuclear fusion energy powers the Sun. The objective of harnessing this seemingly abundant potentially non-radioactive source of energy on Earth has widespread interest. I will discuss: Nuclear fusion in stars and in the Universe; conventional approaches to realize it on Earth including the ITER experimental plasma reactor under construction; and the very big inertial confinement laser at NIF.

However, these large efforts require tritium: The unstable tritium fuel generates lethal weapon grade neutrons and needs to be artificially created. I will refocus attention and discuss pros and cons of three modern fusion paths operating outside of thermal equilibrium constraints: Muon catalyzed nuclear fusion; Laser driven proton acceleration used to spark micro-explosion fusion; and laser driven coherent plasmon field induced fusion. The last two approaches are relying on alternative light element fuels available for mining and are operating in an aneutronic manner.
1973: PhD from Frankfurt University with specialty in theoretical nuclear physics
2011–2015: pB fusion and lasers
2021–present: Moving into plasmonic fusion

Hydrogenic mesomolecules and muon catalyzed fusion

J. Rafelski
CERN -- Geneva

Abstract

Hydrogenic mesomolecules are discussed with particular emphasis on their role in the muon catalyzed fusion process. Recent theoretical and experimental evidence for weakly bound mesomolecules dμ and dμ derived from resonant mesomolecular formation and its dependence on the temperature is described. The fate of the muon stopped in a 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
We are working on fusion here

Matter in the Universe: Making nuclei

Big Bang nucleosynthesis (first fusion)

Supernova element synthesis (stellar fusion)
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.

The fusion reactor powering the solar system

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

- 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 $3.8 \times 10^{26}$ 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.
The abundance of elements is the outcome of BBN and stellar nucleosynthesis. Hard to make and nuclear burn depleted. Most bound nuclei and thus relatively more abundant. The light elements of lithium, boron and beryllium are suitable for aneutronic fusion. U decays faster than Th so less abundant. Fuel for standard fission reactors.
Fission versus fusion

Fission processes break apart large nuclei

Man-made fission reactor
Pale Verde Generating Station west of Phoenix, AZ

Fusion processes “fuse” or combine smaller nuclei into larger ones

Natural fusion reactor
Future man-made fusion

Natural fission reactor
Present 2 billion years ago at Oklo, Gabon in Africa

Movie: Passengers (2016)
Manmade fusion awakening
Dozens of government and commercial projects and companies are all chasing 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.

August 2022

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.
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
ITER = International Thermonuclear Experimental Reactor
ITER is a $70 billion experiment: Start 2050?

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

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 require 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

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.”


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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.

... 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...
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)
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.

"Out of gas" (tritium)

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 a large excess amount of tritium required in growing 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.

One experimental reactor burns it all
dt-fusion safety and radioactive waste

Thermal neutron absorber

\[ 14 \text{ MeV} = D = T = d = t \]

\[ \alpha \rightarrow d(14 \text{ MeV}) + n(14 \text{ MeV}) \]

\[ m_n c^2 = 940 \text{ MeV} \]

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

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.


MeV energy units: M = million and eV is the kinetic energy a unit charged particle acquires in a 1 Volt step
The trouble with dt-fusion 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), occasional neutrons carry a fraction of a percent of the total energy and material for fusion can be mined.
Inertial confinement fusion

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

Originally envisioned with heavy ions, but ultimately developed using laser pulses.

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.

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.

The tantalizing fusion 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.

Google revives controversial cold-fusion experiments

Researchers tested mechanisms linked to nuclear fusion at room temperature – but found no evidence for the phenomenon.
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.”

Modern nuclear fusion processes occur under inequilibrium conditions with the objective to spark a nano-fusion explosion which is short lived.
Muon-catalyzed fusion (μCF) cycle

- 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.
B: Laser driven aneutronic proton-boron fusion


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.
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.
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.

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

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

C. Labaune¹, C. Baccou¹, S. Depierreux², C. Goyon², G. Loisel¹, V. Yahia¹ & J. Rafelski³

Laser Contrast Ratio: \( R = \frac{\text{Pulse Intensity}}{\text{Prepulse/peDESTal Intensity}} \)

The laser contrast ratio is a crucial parameter in achieving laser-driven nuclear fusion.
The experimental progress in pB fusion measured in terms of $\alpha$ production.
Why can’t we burn pB in a thermal reactor? 
Comparing neutronic and aneutronic fusion

Some advanced fuels (such as boron) do not allow steady state thermal fusion because of fusion output versus radiation loss.
C: Plasmonic fusion

Antennas for light

Lukas Novotný* and Niek van Hulst

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.

Surface plasmons: a strong alliance of electrons and light

Norbert Kroó1,3, Sándor Varró1,2, Péter Rácz1 and Péter Dombi1,2

Surface plasmon polaritons (SPPs) have several unique properties, including their strong-field enhancing effect in near field. This means, among other things, that nonlinear phenomena may be studied at much lower laser intensities. The present paper describes in detail the theory of basic properties of SPPs, and our model of a laser-induced oscillating double-layer potential. The SPPs may decay into photons and hot electrons. The latter may be emitted by a multi-plasmon process. Experiments on both photon and electron emission from a gold film are briefly
Antenna response: 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.
Antennas for light invented in ancient Imperial Rome

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 NAPlife plasmonic fusion project

NAPlife Collaboration:
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

Demonstration of antenna amplification principle for
purpose of fusion
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.

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).
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
I thank Ryszard Gajewski for infecting me with the desire to realize table-top usable fusion.

I thank: Steven E Jones for happy years of collaboration in muon catalyzed fusion; Christine Labaune for her great leadership and dedication to laser driven non-equilibrium pB fusion.

I thank: László Csernai for his persistent multi-year effort in drawing my attention to plasmonic fusion; L. C., Tamás Biró, Norbert Kroó for teaching me plasmonic fusion; I thank all of them and Péter Lévai for their kind hospitality in Budapest sponsored by the Fullbright Foundation with a travelling professor award and allowing my encounter with the plasmonic fusion project.

I thank Andrew Steinmetz for interest in, and kind assistance with preparation of this talk.

Thank you for your attention!

Johann Rafelski
Appendix
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?

• 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 ($\mu$CF)  Proton-Boron fusion ($pB$)
The proton-proton chain in detail

Diagram showing the proton-proton chain with reactions:
- $p^+ + p^+ \rightarrow ^2\text{H} + e^+ + \nu_e$ (99.77%)
- $p^+ + e^- + p^+ \rightarrow ^2\text{H} + \nu_e$ (0.23%)
- $^2\text{H} + p^+ \rightarrow ^3\text{He} + \gamma$ (10^-5 %)
- $^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma$ (0.1 %)
- $^7\text{Be} + e^- \rightarrow ^7\text{Li} + \nu_e$ (99.9 %)
- $^7\text{Be} + p^+ \rightarrow ^8\text{B} + \gamma$ (15.08 %)
- $^8\text{B} \rightarrow ^8\text{Be}^* + e^+ + \nu_e$
- $^8\text{Be}^* \rightarrow ^4\text{He} + ^4\text{He}$
Secondary power source of our Sun: The CNO cycle

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

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

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

Lesson for laboratory fusion!
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.


- III-D: Pulsed laser aneutronic pB fusion

- III-E: Plasmonic fusion (with pulsed lasers)
  Begins in 2021: NAPlife project. Concentrations of light energy with nanorods: Antennas for light!
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.

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

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

\[ \# \text{ of fusions to produce } 1 \text{ W} = \frac{6.24 \times 10^{18} \text{ eV}}{17.6 \text{ MeV}} = 3.55 \times 10^{11} \text{ dt fusions/second} \]

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 \(160 \text{ kg of tritium per year}.\)

\[ 6.02 \times 10^{23} \text{ tritons} \approx 3 \text{ grams} \]
Different $\mu$CF 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.

<table>
<thead>
<tr>
<th>MuCF hydrogen fusion reactions.</th>
<th>S-wave</th>
<th>P-wave</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p + d$ (μ) $\rightarrow$</td>
<td>$\sim 52%$</td>
<td>$42%$</td>
</tr>
<tr>
<td>$d + d$ (μ) $\rightarrow$</td>
<td>$\sim 48%$</td>
<td>$58%$</td>
</tr>
<tr>
<td>$p + t$ (μ) $\rightarrow$</td>
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</tr>
<tr>
<td>$d + t$ (μ) $\rightarrow$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t + t$ (μ) $\rightarrow$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- $\sim 0.84\%$  
  $3\text{He} \ (5.4 \text{ keV}) + \gamma \ (5.48 \text{ MeV})$
- $\sim 16\%$  
  $3\text{He} \ (0.20 \text{ MeV}) + \mu \ (5.29 \text{ MeV})$
- $t \ (1.01 \text{ MeV}) + p \ (3.02 \text{ MeV})$
- $3\text{He} \ (0.82 \text{ MeV}) + n \ (2.45 \text{ MeV})$
- $4\text{He} \ (52 \text{ keV}) + \gamma \ (19.76 \text{ MeV})$
- $4\text{He} \ (3.56 \text{ MeV}) + n \ (14.03 \text{ MeV})$
- $4\text{He} + n + n \ (11.33 \text{ MeV})$
### Muon catalysed fusion

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$Q$</th>
<th>$\mu$</th>
<th>$\log(D_{1s\sigma})$</th>
<th>$\log(\lambda)$</th>
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<td>6</td>
<td>625</td>
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<td>853</td>
<td>-6 (-5)</td>
<td>12 (13)</td>
</tr>
<tr>
<td>$^{10}\text{Be} + d$</td>
<td>13</td>
<td>1562</td>
<td>-8 (-7)</td>
<td>10 (11)</td>
</tr>
<tr>
<td>$^{10}\text{Be} + t$</td>
<td>11</td>
<td>2159</td>
<td>-10 (-9)</td>
<td>8 (9)</td>
</tr>
</tbody>
</table>

$Q$ values (MeV) of the fusion reactions, reduced mass $\mu$ (MeV) of the nuclear system, 1s$\sigma$ penetration constant $D_{1s\sigma}$, and an estimate of the reduced direct nuclear reaction rate $\lambda$ (s$^{-1}$). 'Optimistic' and 'pessimistic' values of 0.5 and 1 were selected for $\epsilon$, the optimistic values appearing in parentheses. Symmetry and quantum number selection rules have been disregarded.


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Search for aneutronic $\mu$CF

All possible light element fusion reactions

Much work can still be done in this field!

Resonant mesomolecular processes would need to be discovered.
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.
Why boron-nitride?

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 + ^{10}\text{B} \rightarrow 3\alpha + 8.7 \text{ MeV}), is one of the most attractive aneutronic fusion reactions. 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}\text{B} can also occur but are not shown for clarity.
Owing to their unique laser light energy concentration properties, nanoparticles 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...

Technological applications of plasmonics phenomenon

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).

([Chemical structures and diagrams])

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 = Triethyenglycol-dimethacrylat; mm = Millimeter)
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**

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.

**Plasmonic nuclear fusion**

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

Recap:

- $\mu CF$ 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

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
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 not 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