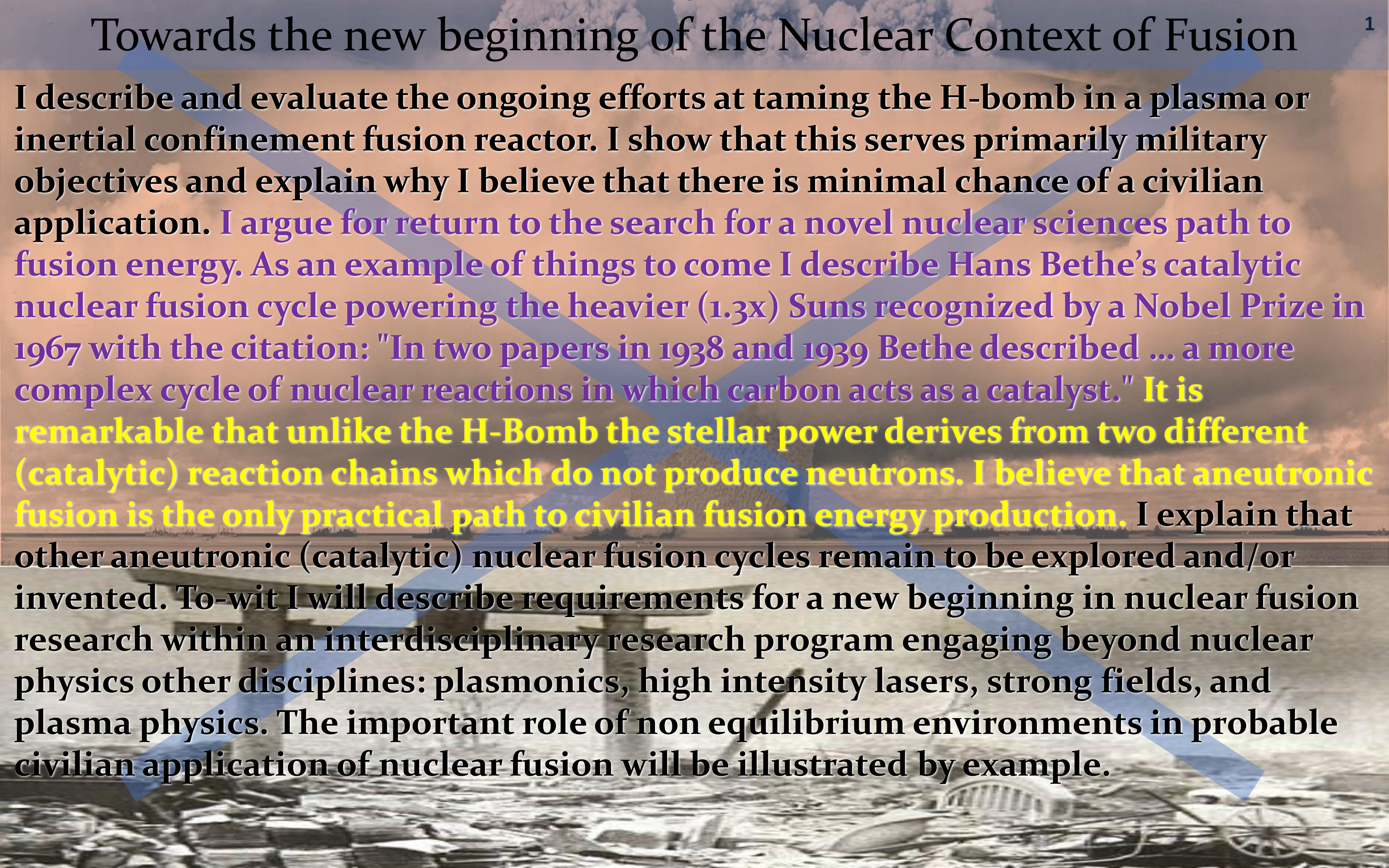
Towards the new beginning of the Nuclear Context of Fusion



I describe and evaluate the ongoing efforts at taming the H-bomb in a plasma or inertial confinement fusion reactor. I show that this serves primarily military objectives and explain why I believe that there is minimal chance of a civilian application. I argue for return to the search for a novel nuclear sciences path to fusion energy. As an example of things to come I describe Hans Bethe's catalytic nuclear fusion cycle powering the heavier (1.3x) Suns recognized by a Nobel Prize in 1967 with the citation: "In two papers in 1938 and 1939 Bethe described … a more complex cycle of nuclear reactions in which carbon acts as a catalyst." It is remarkable that unlike the H-Bomb the stellar power derives from two different (catalytic) reaction chains which do not produce neutrons. I believe that aneutronic fusion is the only practical path to civilian fusion energy production. I explain that other aneutronic (catalytic) nuclear fusion cycles remain to be explored and/or invented. To-wit I will describe requirements for a new beginning in nuclear fusion research within an interdisciplinary research program engaging beyond nuclear physics other disciplines: plasmonics, high intensity lasers, strong fields, and plasma physics. The important role of non equilibrium environments in probable civilian application of nuclear fusion will be illustrated by example.

Nuclear Context of Fusion

Putting **Good** Nuclear Physics Back into Nuclear Fusion

Presented at the
Particles & Plasmas 2023
Margaret Island Symposium
June 7th-9th

Johann Rafelski

THE UNIVERSITY OF ARIZONA
Department of Physics

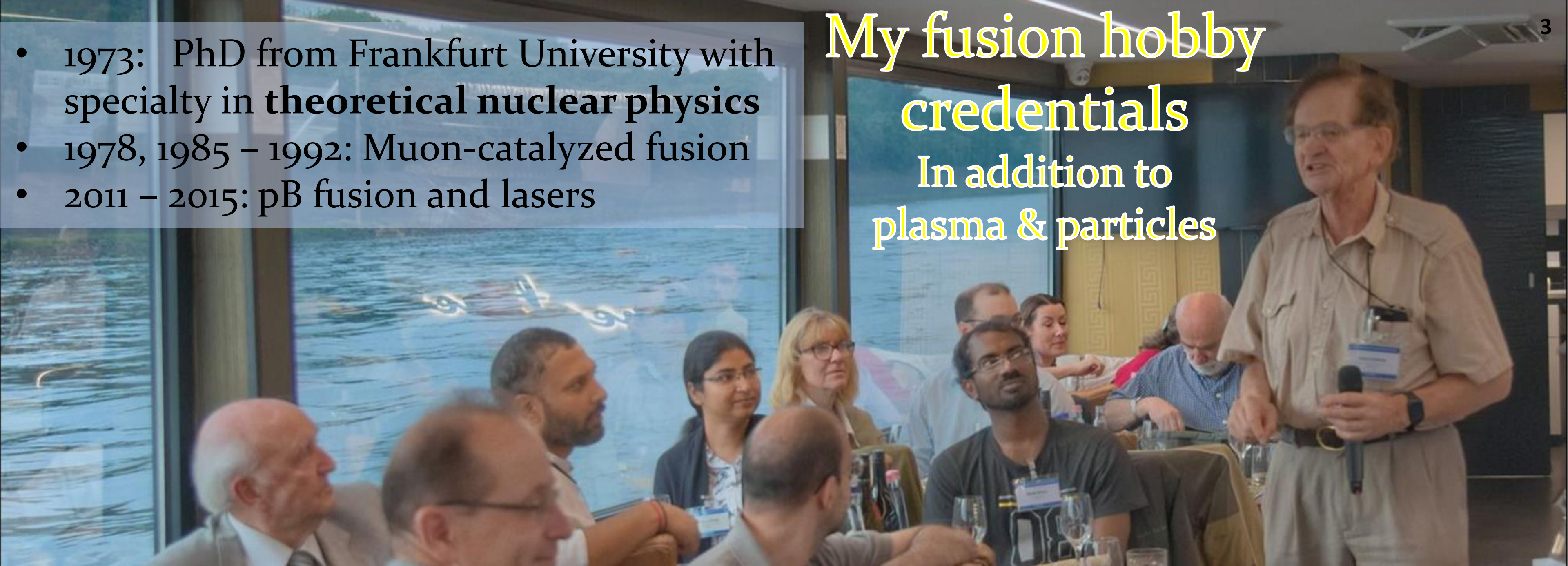
Budapest; Photo by László Pál Csernai 2019

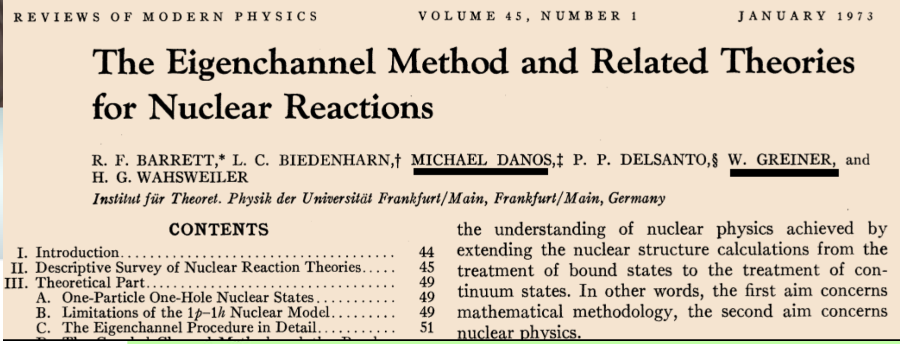
Liberty Square, Budapest

My fusion hobby credentials

In addition to plasma & particles

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





REVIEWS OF MODERN PHYSICS VOLUME 45, NUMBER 1 JANUARY 1973

The Eigenchannel Method and Related Theories for Nuclear Reactions

R. F. BARRETT,* L. C. BIEDENHARN,† MICHAEL DANOS,‡ P. P. DELSANTO,§ W. GREINER, and H. G. WAHSWEILER

Institut für Theoret. Physik der Universität Frankfurt/Main, Frankfurt/Main, Germany

CONTENTS

the understanding of nuclear physics achieved by extending the nuclear structure calculations from the treatment of bound states to the treatment of continuum states. In other words, the first aim concerns mathematical methodology, the second aim concerns nuclear physics.

nature COMMUNICATIONS

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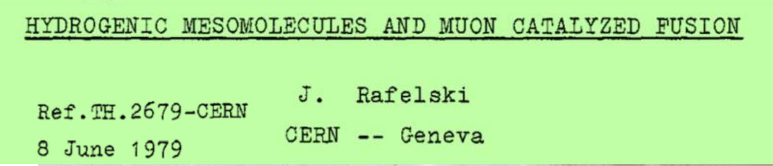
DOI: 10.1038/ncomms3506

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]



HYDROGENIC MESOMOLECULES AND MUON CATALYZED FUSION

J. Rafelski

Ref.TH.2679-CERN

CERN -- Geneva

8 June 1979

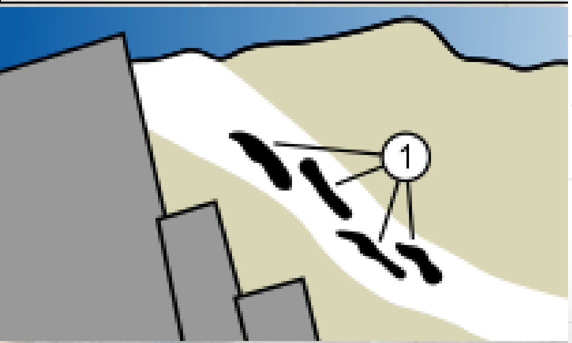
Nuclear fission is different from nuclear fusion

Fission processes break heavy nuclei (U) apart

Fusion processes transmute light nuclei ($pB \rightarrow 3\alpha$)

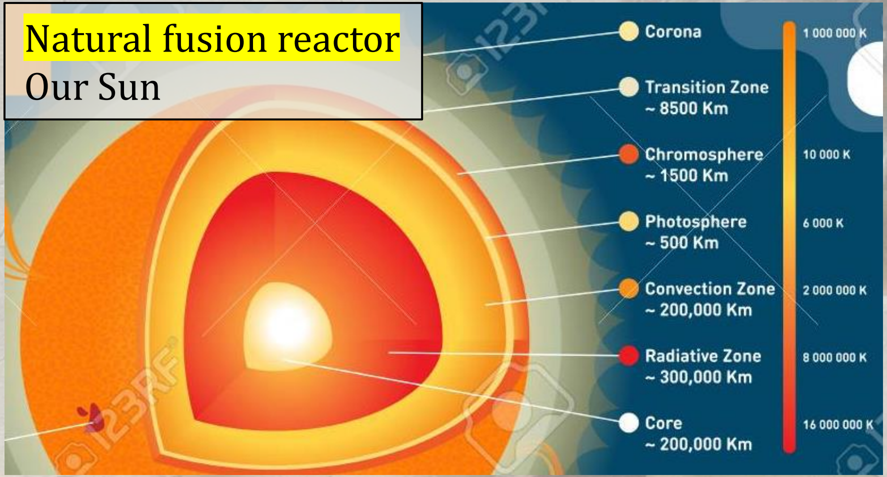
Natural fission reactor

Present 2 billion years ago at Oklo, Gabon in Africa



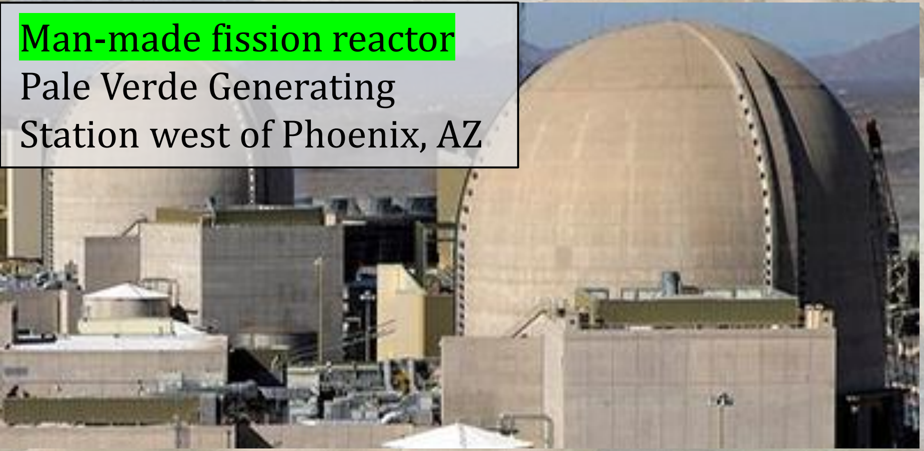
Natural fusion reactor

Our Sun



Man-made fission reactor

Pale Verde Generating
Station west of Phoenix, AZ

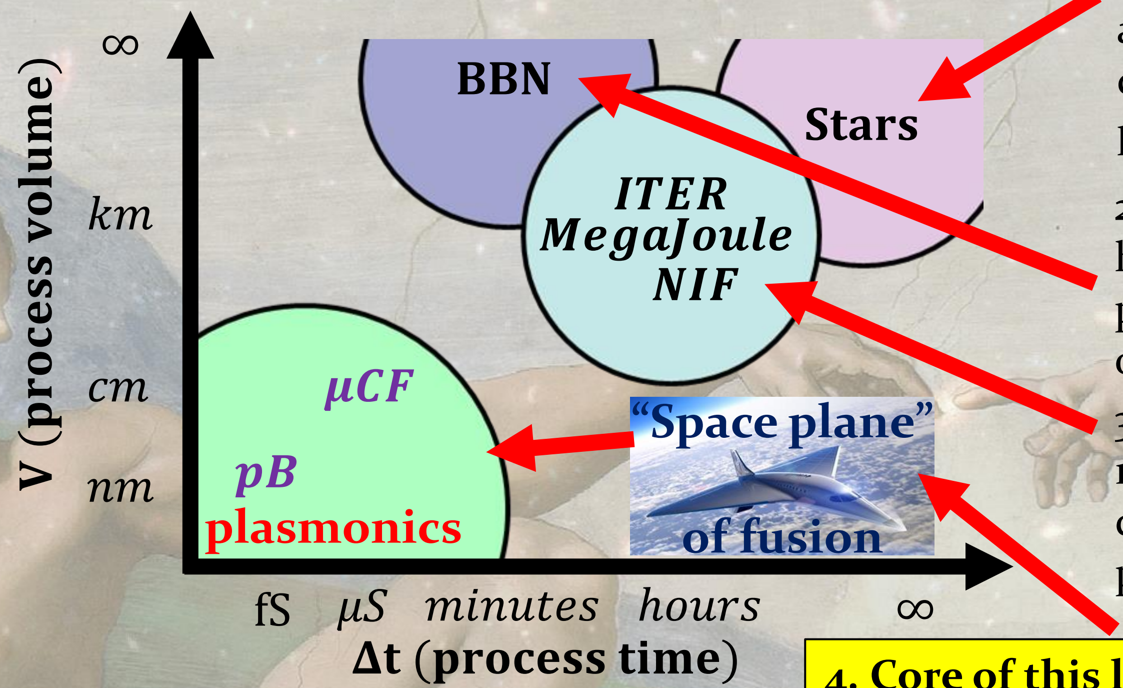


Future man-made fusion

Movie: Passengers (2016)

There are different nuclear fusion environs natural and (planned) manmade

We will address the following four areas of nuclear fusion:



1. Most stellar nucleosynthesis is an equilibrium process which is continuous and stable over large periods of time.

2. Big Bang Nucleosynthesis (BBN) in a homogenous thermally equilibrated plasma which is dynamic and expands over time.

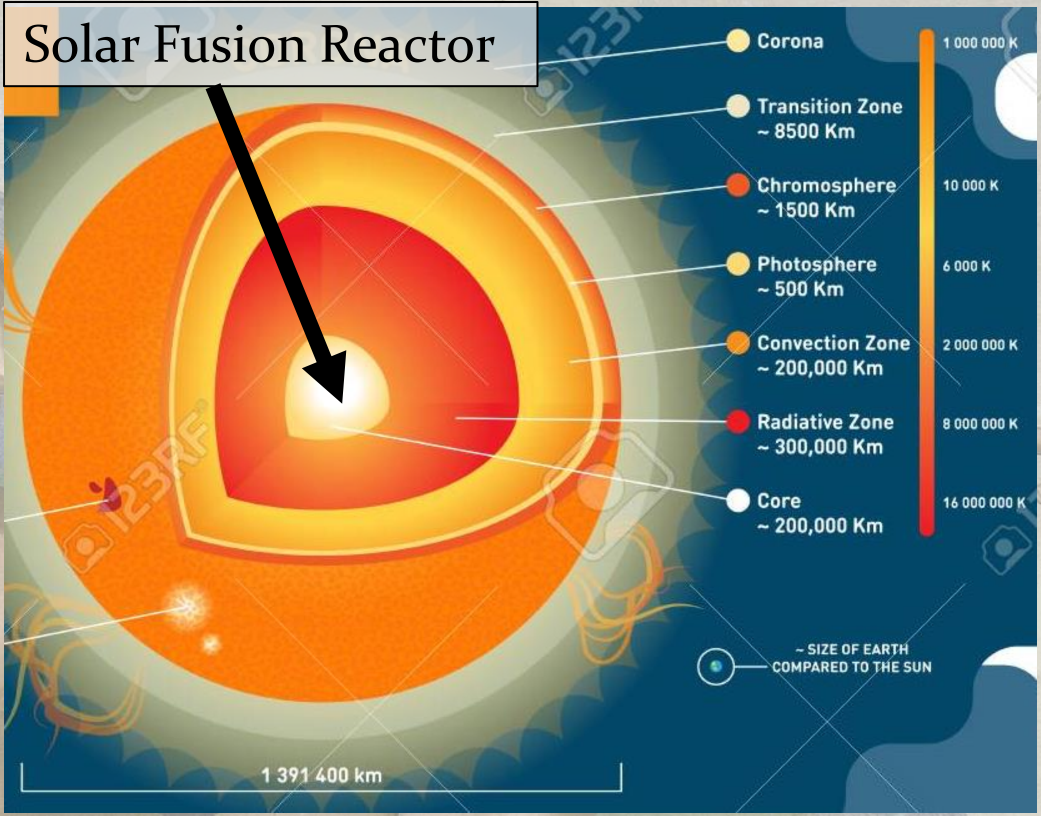
3. Some larger manmade fusion reactors **"H-bomb style"** are designed to operate for short pulsed periods of time.

4. Core of this lecture: Can we facilitate nuclear fusion via a different path as compared to the bomb? Example: Proton-Boron fusion (*pB*)

(*μCF*) = Muon-catalyzed fusion

1 The fusion reactor powering the solar system

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

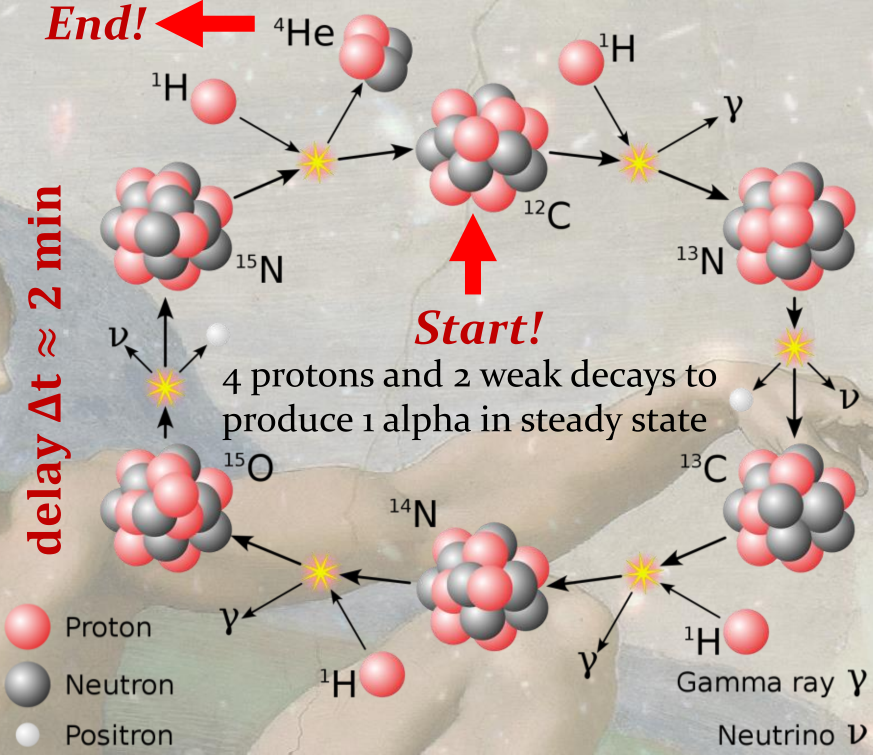


Solar Fusion Reactor

- The Sun produces energy by converting hydrogen into helium-4. Two processes are well known:
  - Proton-Proton (PP) chain
  - Carbon-Nitrogen-Oxygen (CNO) cycle (Only possible for recent stars with recycled ashes)
- 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.

Lesson #1: If you want to work on fusion, know how stars burn.

"Bottling the Sun" is a rich diverse field of study. See 1967 Nobel Prize for H. Bethe's carbon-cycle, an example of **catalytic aneutronic fusion**



End!

Start!

4 protons and 2 weak decays to produce 1 alpha in steady state

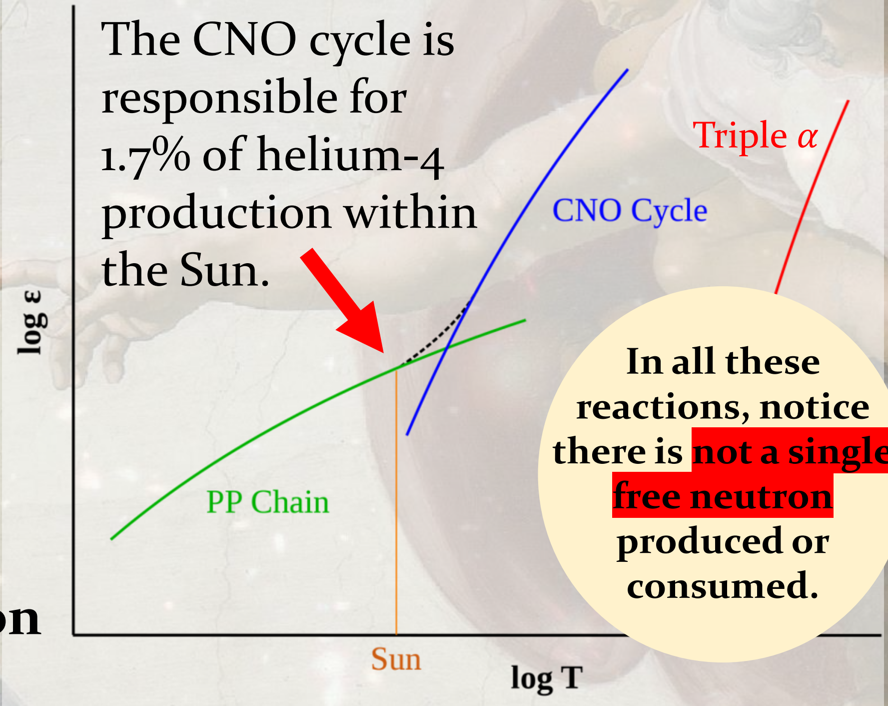
delay Δt ≈ 2 min

deylay Δt ≈ 10 min

"Cooking" hydrogen in carbon evaporating helium!

Graphics courtesy of Wikipedia

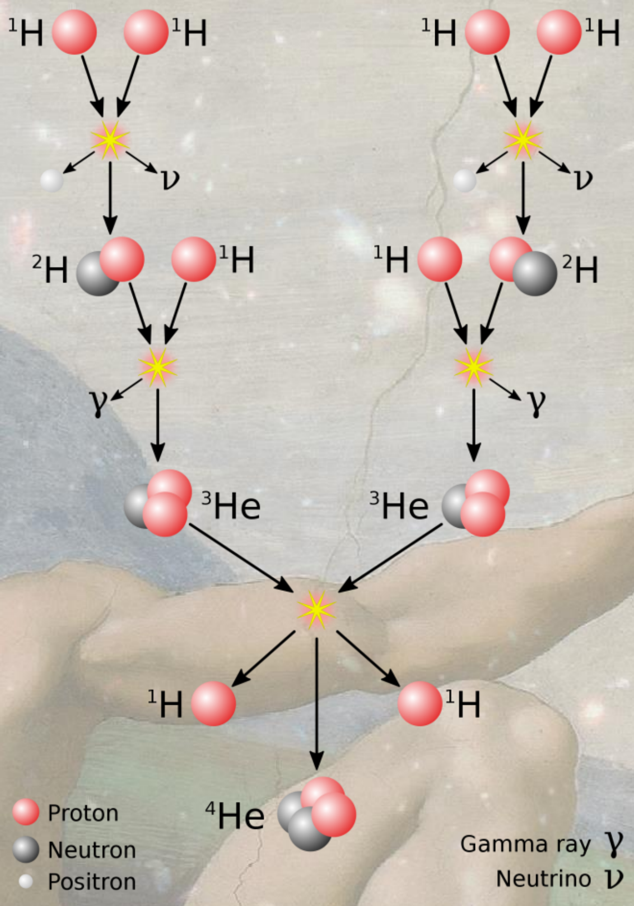
The CNO process overtakes the PP chain for stars above 1.3 solar masses.



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

In all these reactions, notice there is not a single free neutron produced or consumed.

Primary power source of our Sun: The aneutronic P-P chain



Graphic courtesy of Wikipedia

- We note that both PP and CNO stellar burn processes are aneutronic. Another manifestation of the anthropic principle?

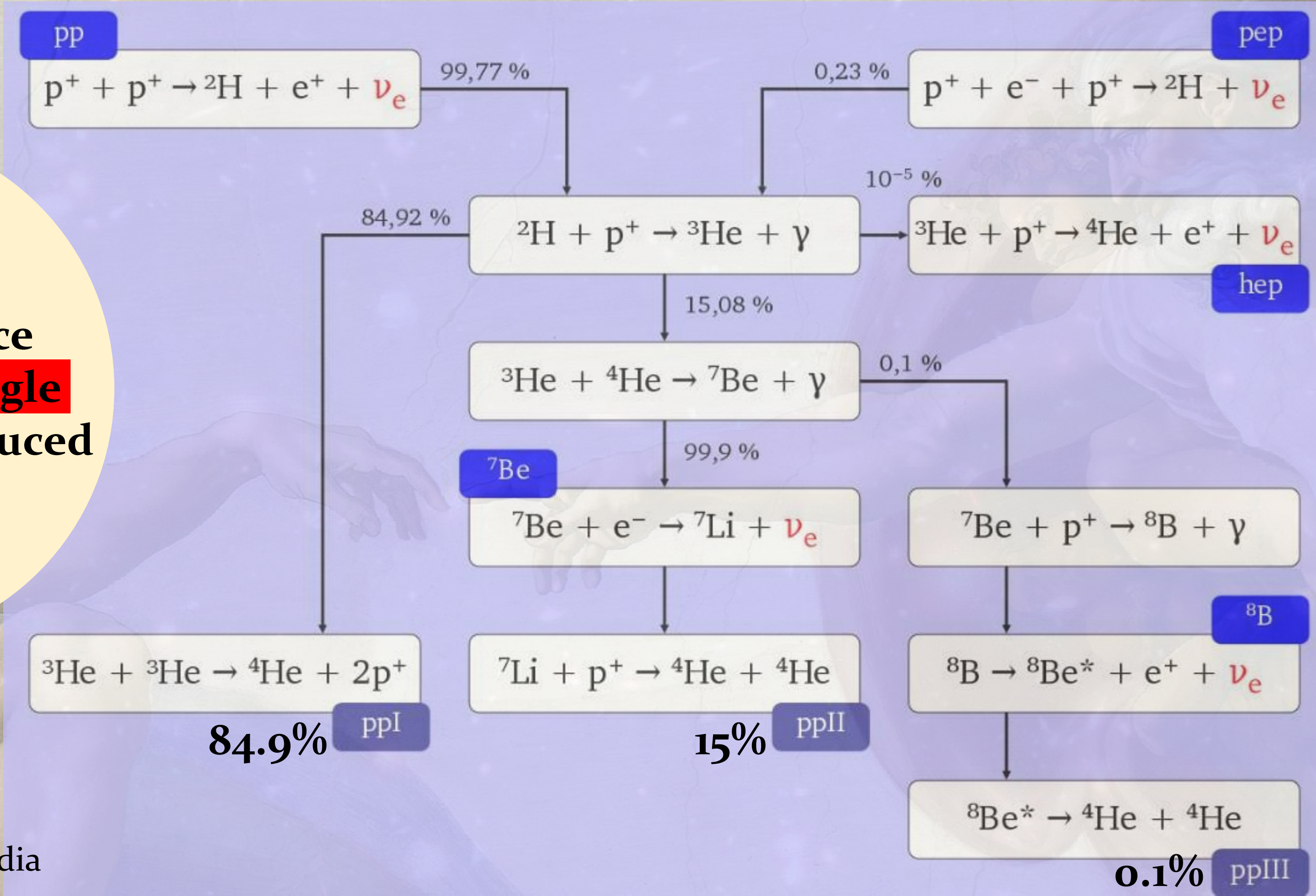
- This process is responsible for most of the energy production within our Sun as well as most low-mass stars.

- Every alpha produces releases about 27 MeV of energy from the binding energy.

- The PP chain uses both the weak and strong interactions:
  - The **very slow** weak interaction converts two protons in the first step into one deuteron.
  - The strong interaction then accomplishes the second and third steps to make intermediate helium-3 and finally the product helium-4.

The proton-proton chain in detail

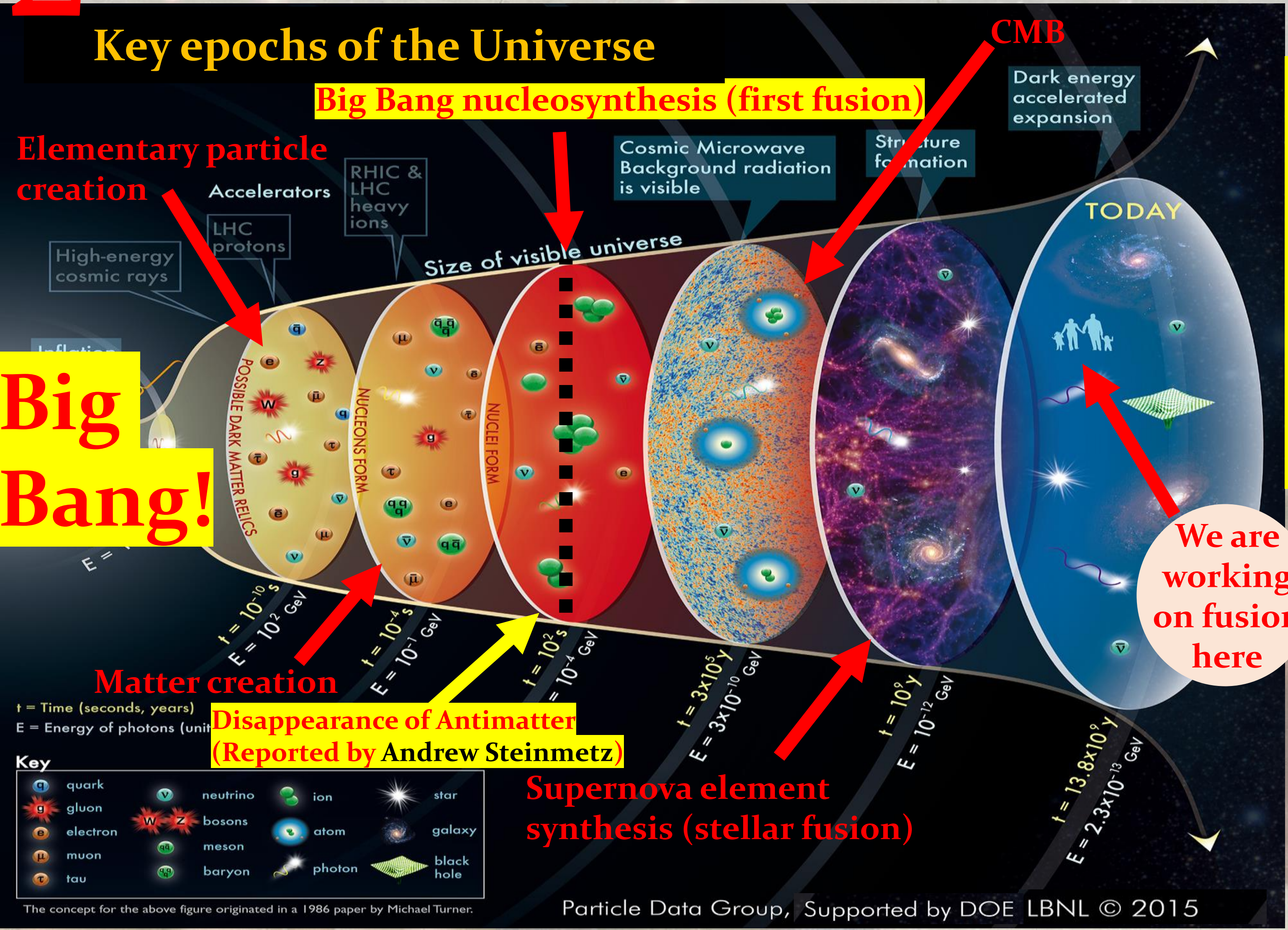
In all these reactions, notice there is not a single free neutron produced or consumed.



Graphic courtesy of Wikipedia

2 Particles and Plasmas in the Universe: Making matter and nuclei

Key epochs of the Universe



The concept for the above figure originated in a 1986 paper by Michael Turner.

Particle Data Group, Supported by DOE LBNL © 2015

Big Bang!

Elementary particle creation

Big Bang nucleosynthesis (first fusion)

CMB

Matter creation

Disappearance of Antimatter (Reported by Andrew Steinmetz)

Supernova element synthesis (stellar fusion)

We are working on fusion here

A short survey of matter-antimatter evolution in the primordial universe

J. Rafelski, J. Birrell, A. Steinmetz, C.-T. Yang

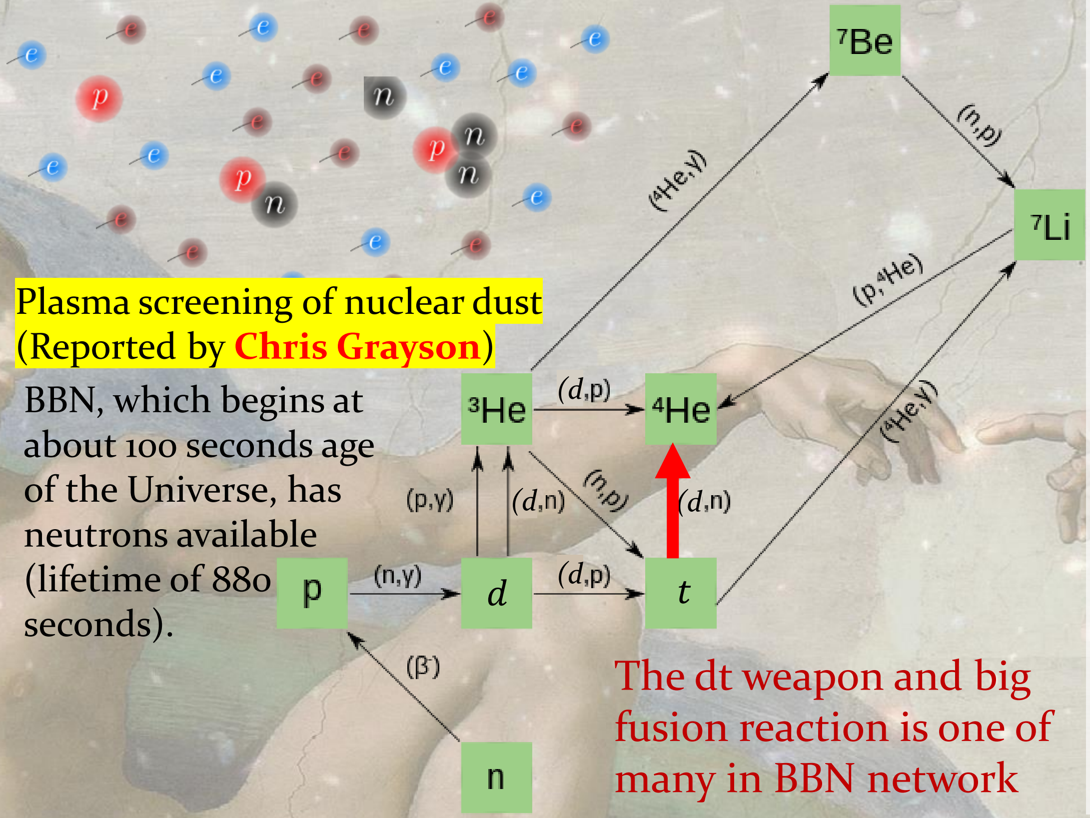
arXiv: 2305.09055

The first nuclear burn in the universe:

Big Bang nucleosynthesis

It would be nice if: BBN would be responsible for the generation of the light elements (α, Li, B, Be) while heavier elements are products of stellar life and death.

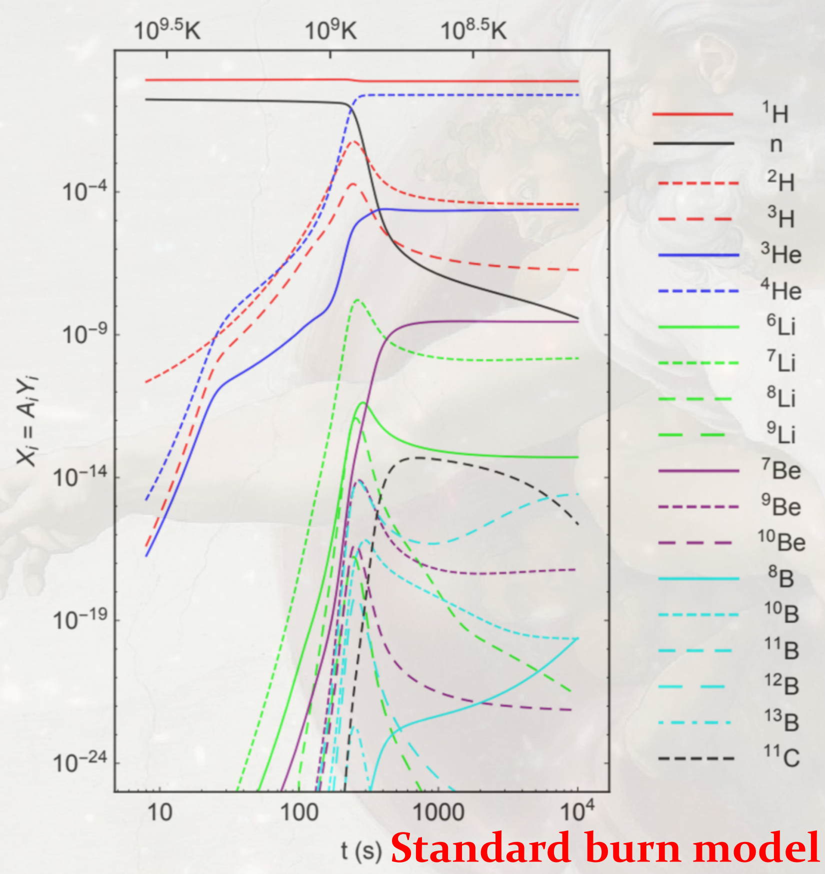
BBN is an example of fusion network is neither related to the Sun or the weapon.



Plasma screening of nuclear dust (Reported by **Chris Grayson**)

BBN, which begins at about 100 seconds age of the Universe, has neutrons available (lifetime of 880 seconds).

The dt weapon and big fusion reaction is one of many in BBN network



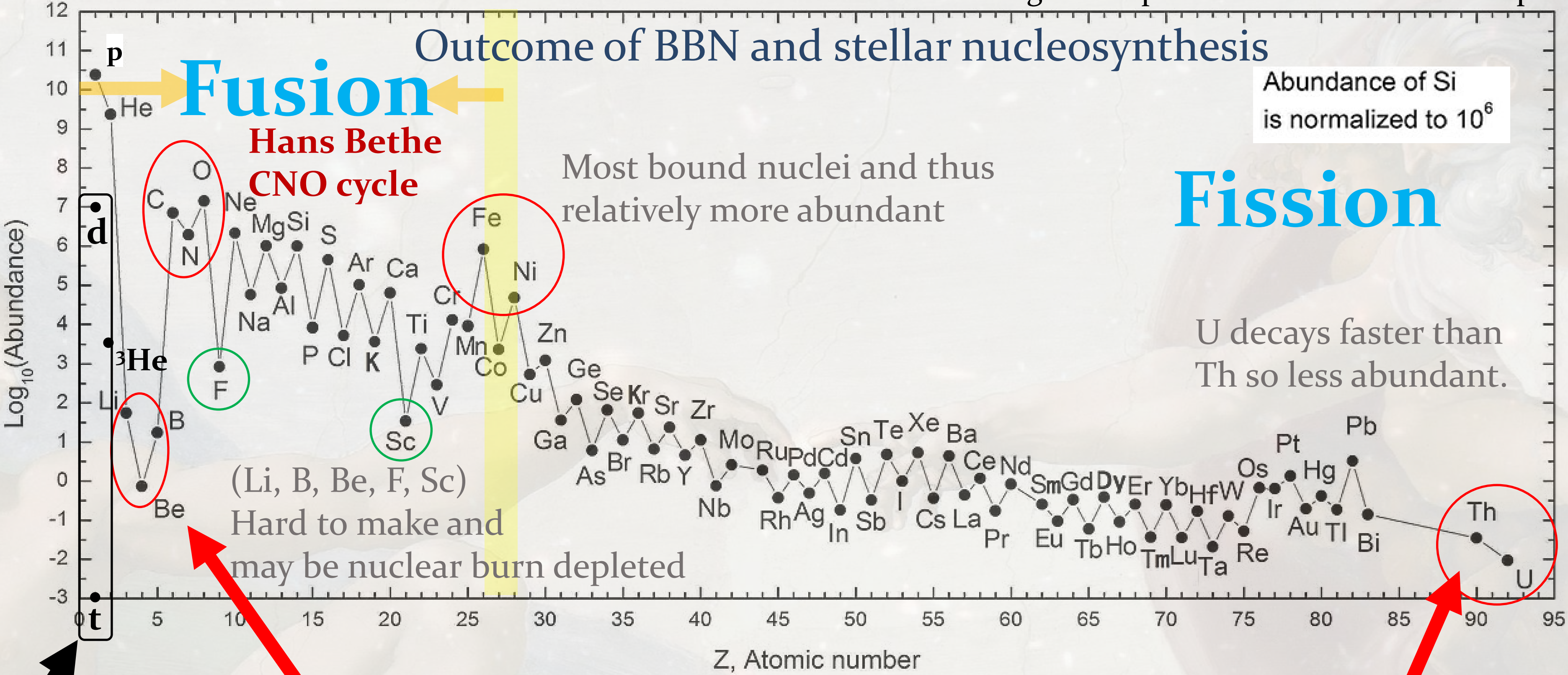
Standard burn model

C. Pitrou, et al. "Precision BBN…" Physics Reports 754 (2018): 1-66.

Present day nuclear ashes in the Universe And their role in energy production

Distribution due to non-equilibrium processes. Future equillibrium yields mostly nickel and iron – in zillions of years, if at all.

Figure adapted and evolved from Wikipedia



Fusion

Hans Bethe CNO cycle

Most bound nuclei and thus relatively more abundant

Fission

U decays faster than Th so less abundant.

(Li, B, Be, F, Sc) Hard to make and may be nuclear burn depleted

H-bomb and ITER

Some light elements such as boron or beryllium can serve in aneutronic fusion cycle.

Fuel for standard fission reactors

3 Inertial confinement indirect drive fusion

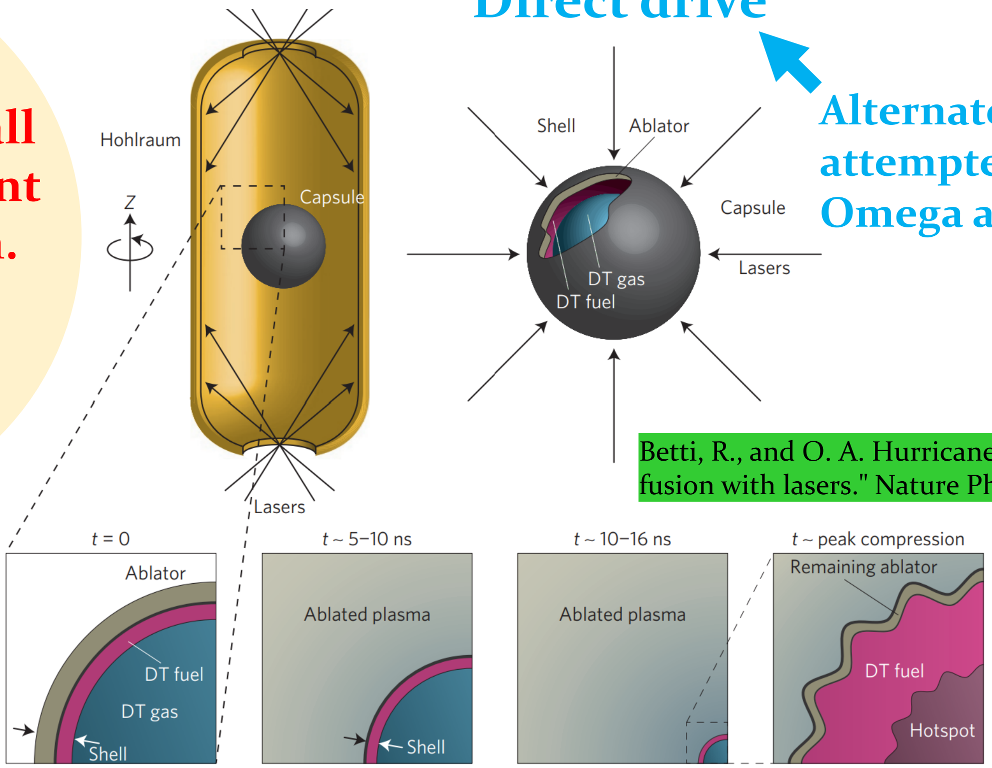
Exact imitation of micro-Nuclear Weapon with high power lasers

Alert #1: dt-fusion is “bottling the H-bomb”

REVIEW ARTICLES | INSIGHT NATURE PHYSICS DOI: 10.1038/NPHYS3736

Indirect drive

Direct drive



Problems with tritium and neutrons apply to all inertial confinement and plasma fusion.

Weapon neutrons used to breed tritium from lithium.

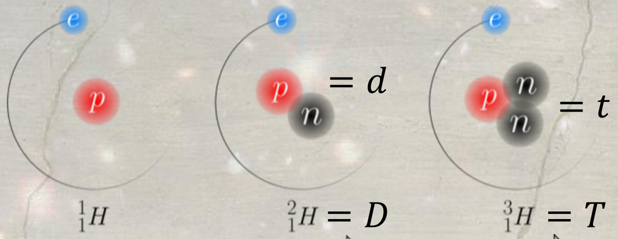
Alternate process attempted by NIF, Omega and Megajoule

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

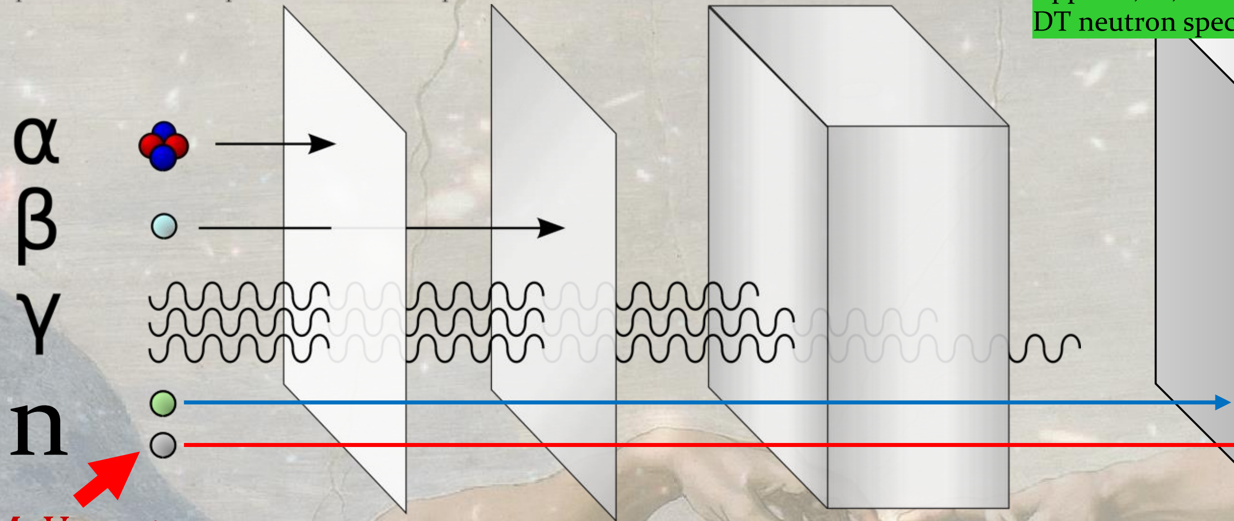
Originally envisioned with heavy-ions, but ultimately developed using laser pulses.

Trouble with bottling the weapon

Alert #2: dt-fusion creates safety concerns and a lot of radioactive waste



Appelbe, B., and J. Chittenden. "Relativistically correct DD and DT neutron spectra." High Energy Density Physics 11 (2014): 30-35.



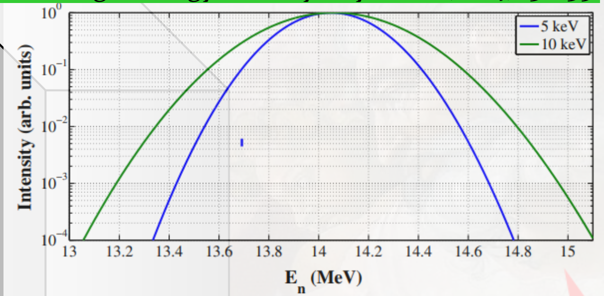


Fig. B.4. The DT neutron spectrum for ion temperatures of 5 keV and 10 keV showing the asymmetry of the spectrum with a greater intensity in the high-energy tail compared to the low-energy tail of the spectrum.

14 MeV neutrons
(dt process)
$v_n = 0.173c$

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

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

dt-fusion leads to super-fast neutrons and associated problems: Civilian nuclear fusion should seek the development for energy use aneutronic fusion in a dynamic regime i.e. non-thermal equilibrium, forbidden by brems-losses.

We return to this point below

MeV energy units: M = million and eV is the kinetic energy a unit charged particle acquires in a 1 Volt step

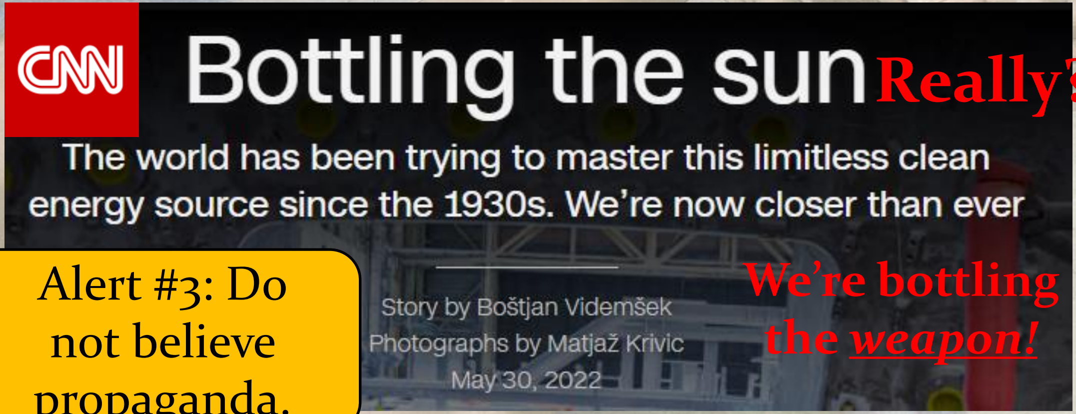
All fusion reactor projects (ITER, etc…) are not "Bottling the Sun"

Fusible materials used and processes occurring in plasma or inertial fusion have little relation, if at all, to fusion reactions within our Sun, or in any other stellar object. Maybe the purpose of current inertial confinement and/or plasma fusion is to imitate nuclear weapons in near equilibrium burn process.

Money flow from US DOE/DOD (weapons programs)

There are large technical problems:

It is commonly believed that civilian fusion programs began **before** there was adequate understanding of the required science and technology. People in charge of developing fusion energy are trained in engineering, material science, and management while making decisions about yet-to-be understood nuclear technology concepts.



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

Really?

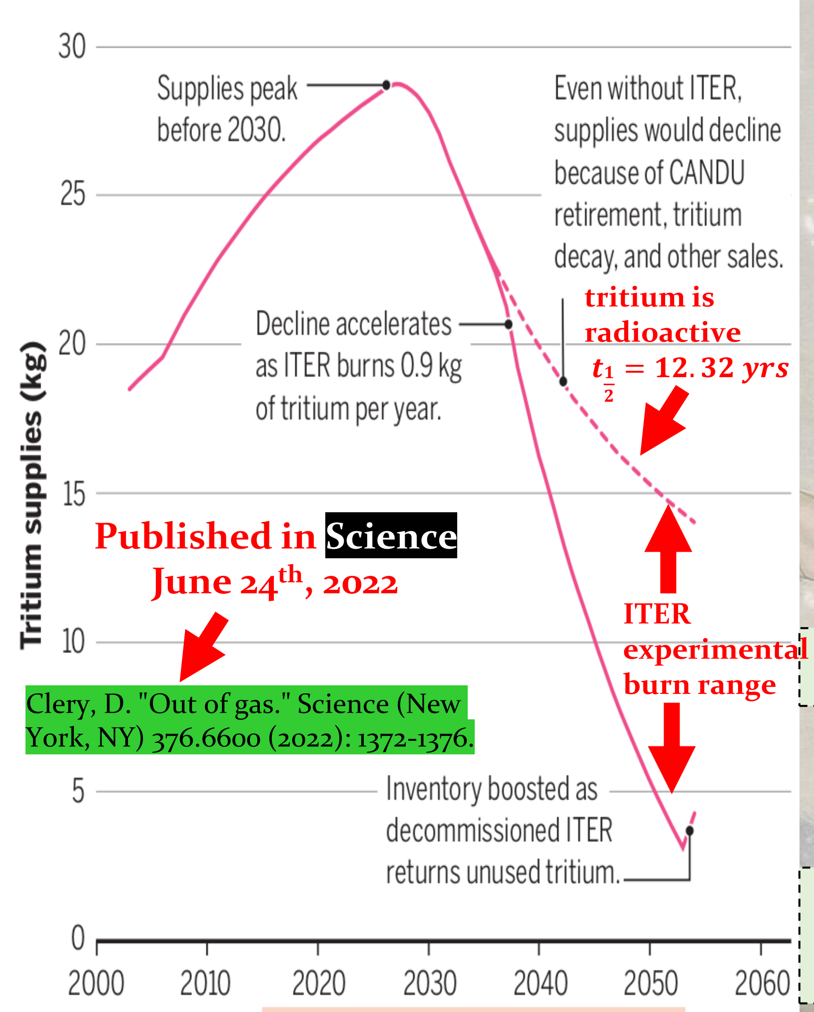
We're bottling the *weapon!*

Alert #3: Do not believe propaganda.

ITER: Risky project at gigantic size with exploding cost.

Alert #4: One experimental reactor (ITER) burns it all.

The trouble with tritium supply



$t_{\frac{1}{2}} = 12.32\ yrs$

Published in Science June 24th, 2022

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

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

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

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

$$\mathbf{1\ W} \mathrel{\hat{=}} \mathbf{3.55 \times 10^{11}}\,\frac{\textbf{dt fusions}}{\textbf{second}}$$

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**.

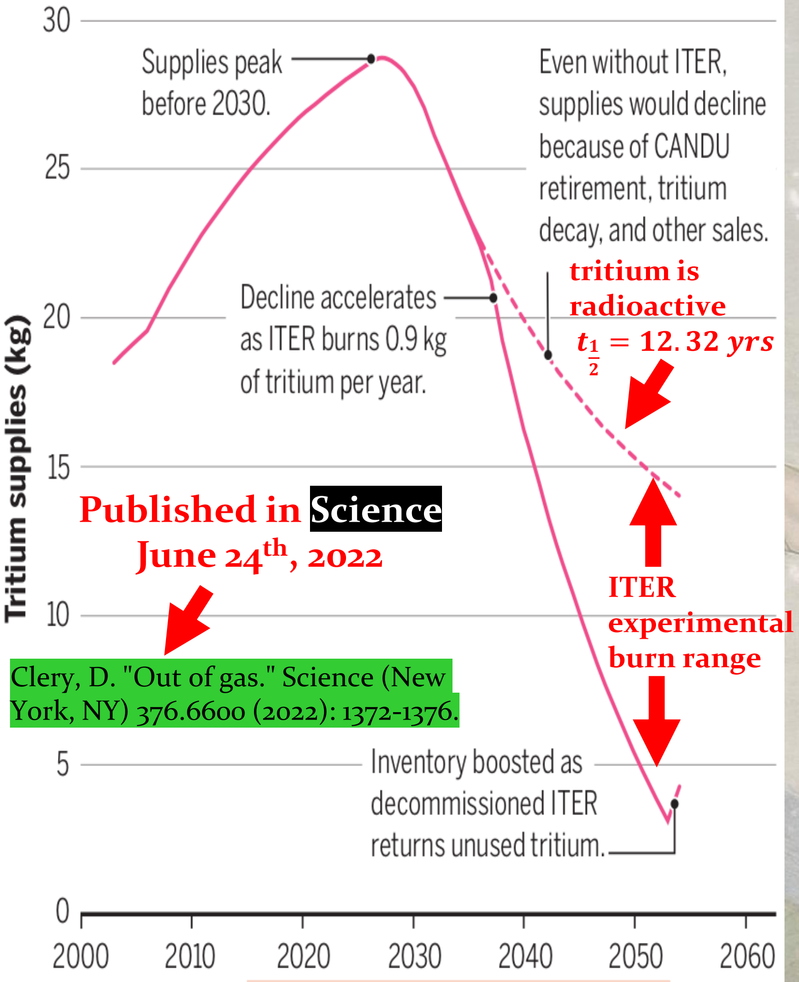
$$6.02 \times 10^{23}\ \text{tritons} \mathrel{\hat{=}} 3\ \text{grams}$$

Cost of artificially made tritium per gram:

$30,000-$300,000

“Out of gas” (tritium)

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.



$t_{\frac{1}{2}} = 12.32\ yrs$

Published in Science
June 24th, 2022

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

Today there is not enough tritium fuel to initiate one reactor.

The tritium producing CANDU fission reactors are being shut off.

Active CANDU reactors [edit]

Today there are 31 CANDU reactors in use around the world, and 13 "CANDU-derivatives" in India, developed from the CANDU design. After India detonated a nuclear bomb in 1974, Canada stopped nuclear dealings with India. The breakdown is:

- Canada: 19 and 5 decommissioned.
- South Korea: 3, and 1 shutdown.
- China: 2
- India: 2, 13 active CANDU-derivatives, and 5 CANDU-derivatives under construction.
- Argentina: 1
- Romania: 2, and 3 dormant part-constructed.
- Pakistan: 1 shutdown.[86]

Breeding a large excess amount of tritium required in growing the dt-fusion economy (with many reactors in a large network) is an unsolved problem and a nuclear proliferation nightmare.

Insight: The dt nuclear fusion energy economy, if technologically realizable, is well beyond a 100-year horizon.

$60 billion on ‘Sunk Cost Fallacy’

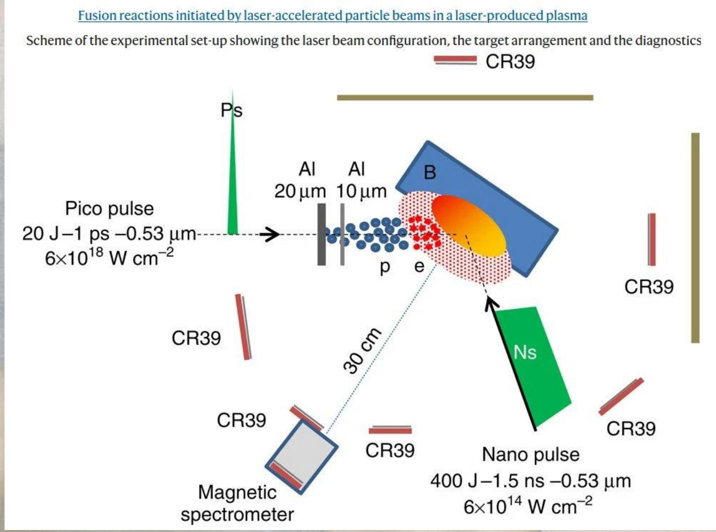
Government bets were placed on the wrong horse.

4

Comparing traditional thermal nuclear fusion to modern nuclear fusion approaches

Modern nuclear fusion processes occur under nonequilibrium conditions with the objective to spark a nano-fusion explosion which is short lived.

LULI pB nuclear fusion

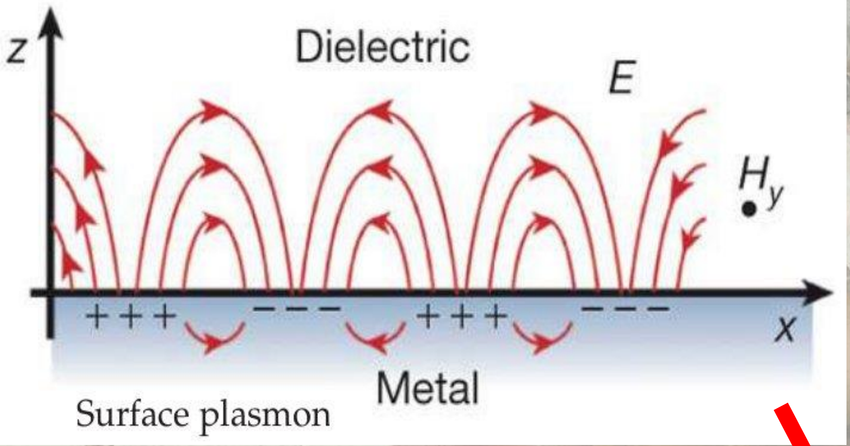


Fusion reactions initiated by laser-accelerated particle beams in a laser-produced plasma

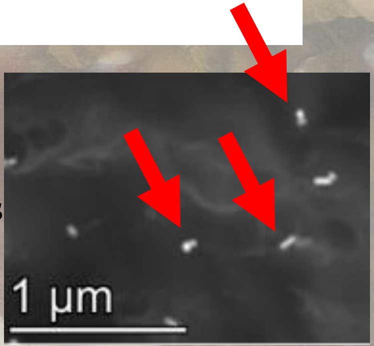
Scheme of the experimental set-up showing the laser beam configuration, the target arrangement and the diagnostics

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



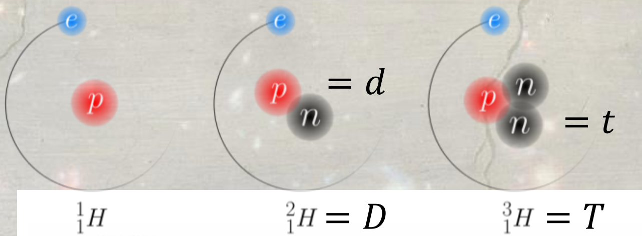
The nano-sized antenna are “energized” to an extreme degree by the incident laser and in the brief moment before the antenna is destroyed, the surface plasmons accelerate particles to required fusion conditions.



Explanation: Why can‘t we burn boron in a steady state thermal reactor?

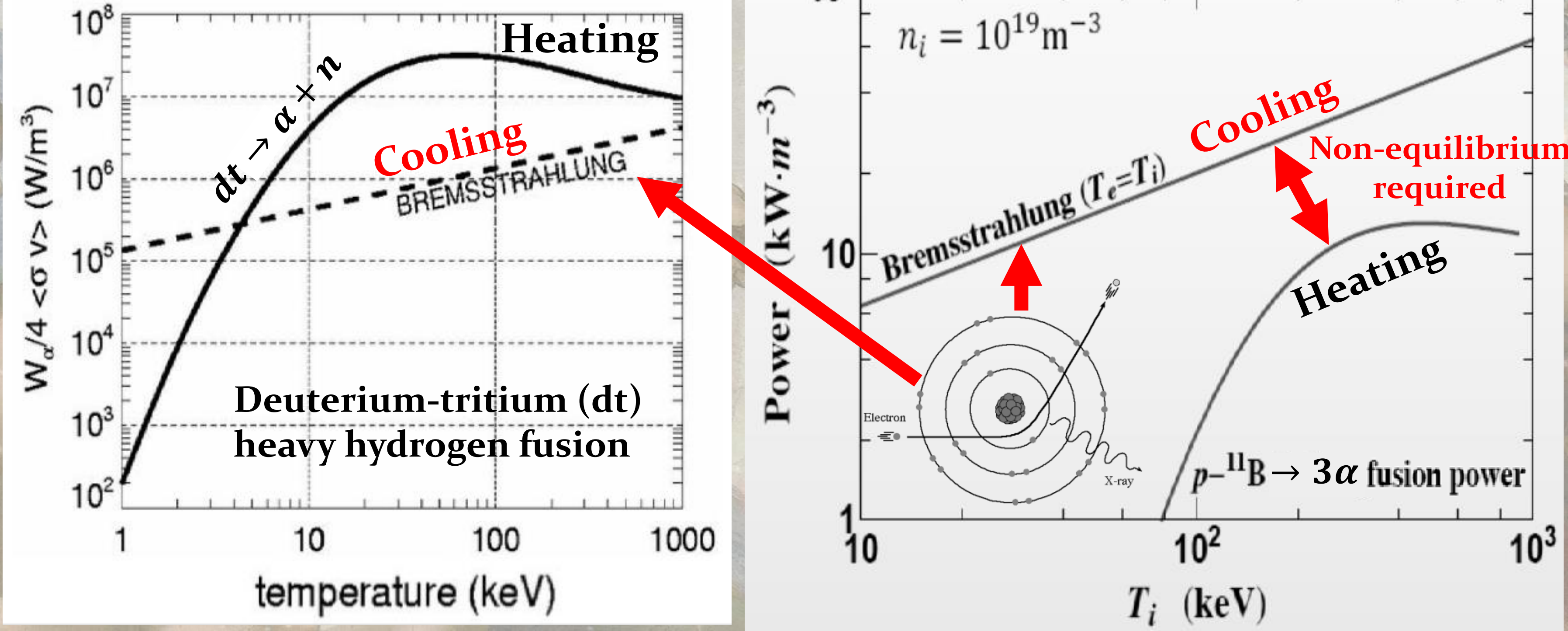
Lesson #2: Currently investigated modern fusion requires non-equilibrium processes.

Comparing neutronic and aneutronic fusion



$$^{11}_{5}B + p \rightarrow 3 \times {}^{4}_{2}He + 16\ \text{MeV}$$

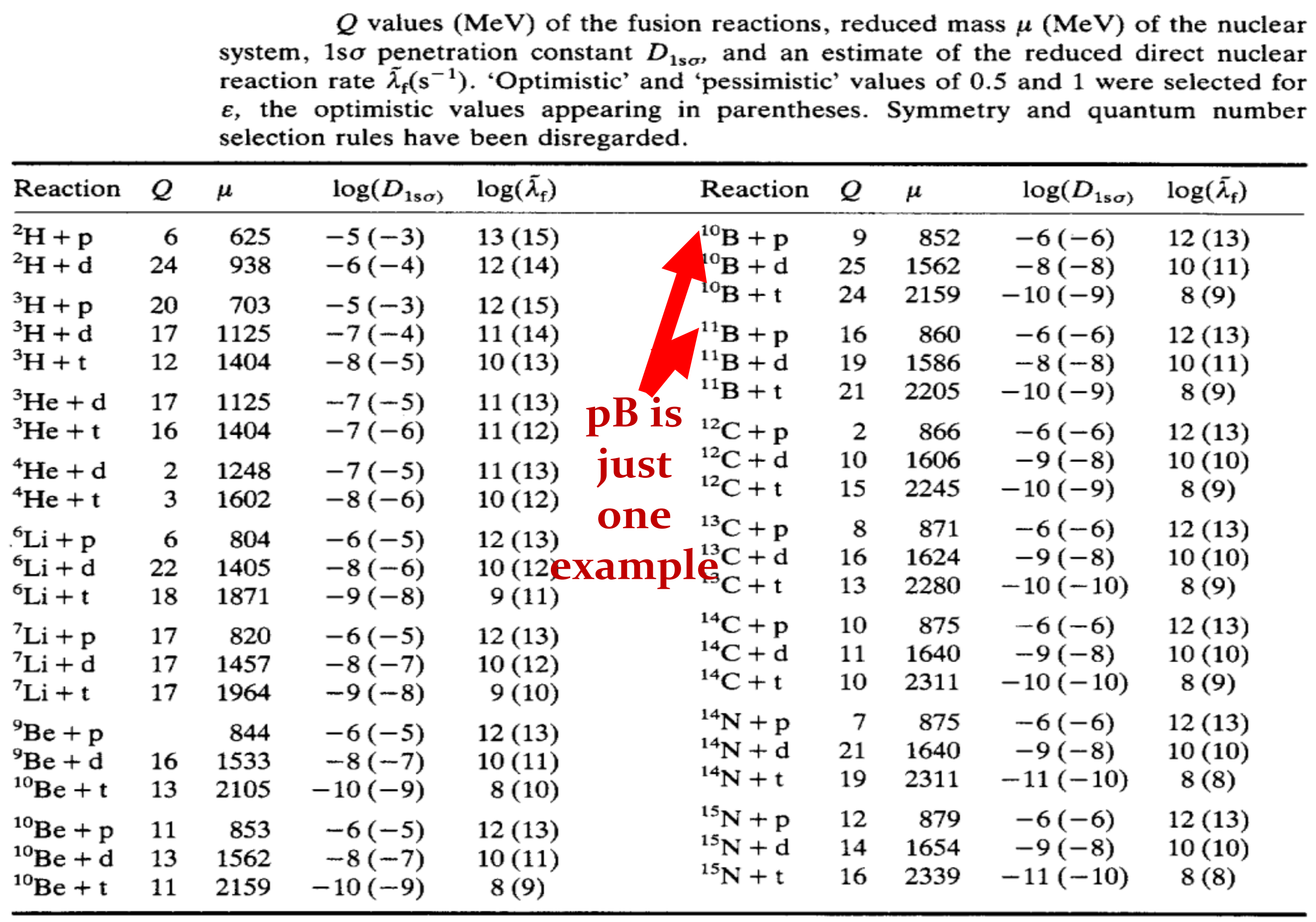
Most advanced fuels (such as boron) do not allow steady state thermal fusion because of fusion output versus radiation loss.



Lesson #3: There are many possible nuclear reactions and zillions of cycles.

Incomplete look at a list of light element fusion reactions

Lots of cooking recipes to be discovered.



Q values (MeV) of the fusion reactions, reduced mass μ (MeV) of the nuclear system, 1sσ 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	$\log(D_{1s\sigma})$	$\log(\tilde{\lambda}_f)$
^{2}H + p	6	625	−5 (−3)	13 (15)
^{2}H + d	24	938	−6 (−4)	12 (14)
^{3}H + p	20	703	−5 (−3)	12 (15)
^{3}H + d	17	1125	−7 (−4)	11 (14)
^{3}H + t	12	1404	−8 (−5)	10 (13)
^{3}He + d	17	1125	−7 (−5)	11 (13)
^{3}He + t	16	1404	−7 (−6)	11 (12)
^{4}He + d	2	1248	−7 (−5)	11 (13)
^{4}He + t	3	1602	−8 (−6)	10 (12)
^{6}Li + p	6	804	−6 (−5)	12 (13)
^{6}Li + d	22	1405	−8 (−6)	10 (12
^{6}Li + t	18	1871	−9 (−8)	9 (11)
^{7}Li + p	17	820	−6 (−5)	12 (13)
^{7}Li + d	17	1457	−8 (−7)	10 (12)
^{7}Li + t	17	1964	−9 (−8)	9 (10)
^{9}Be + p		844	−6 (−5)	12 (13)
^{9}Be + d	16	1533	−8 (−7)	10 (11)
^{10}Be + t	13	2105	−10 (−9)	8 (10)
^{10}Be + p	11	853	−6 (−5)	12 (13)
^{10}Be + d	13	1562	−8 (−7)	10 (11)
^{10}Be + t	11	2159	−10 (−9)	8 (9)
^{10}B + p	9	852	−6 (−6)	12 (13)
^{10}B + d	25	1562	−8 (−8)	10 (11)
^{10}B + t	24	2159	−10 (−9)	8 (9)
^{11}B + p	16	860	−6 (−6)	12 (13)
^{11}B + d	19	1586	−8 (−8)	10 (11)
^{11}B + t	21	2205	−10 (−9)	8 (9)
^{12}C + p	2	866	−6 (−6)	12 (13)
^{12}C + d	10	1606	−9 (−8)	10 (10)
^{12}C + t	15	2245	−10 (−9)	8 (9)
^{13}C + p	8	871	−6 (−6)	12 (13)
^{13}C + d	16	1624	−9 (−8)	10 (10)
C + t	13	2280	−10 (−10)	8 (9)
^{14}C + p	10	875	−6 (−6)	12 (13)
^{14}C + d	11	1640	−9 (−8)	10 (10)
^{14}C + t	10	2311	−10 (−10)	8 (9)
^{14}N + p	7	875	−6 (−6)	12 (13)
^{14}N + d	21	1640	−9 (−8)	10 (10)
^{14}N + t	19	2311	−11 (−10)	8 (8)
^{15}N + p	12	879	−6 (−6)	12 (13)
^{15}N + d	14	1654	−9 (−8)	10 (10)
^{15}N + t	16	2339	−11 (−10)	8 (8)

pB is just one example

This list was prepared for cycles relevant to muon catalyzed fusion. But many more cycles are likely to exist requiring imagination outside the examples nature provides.

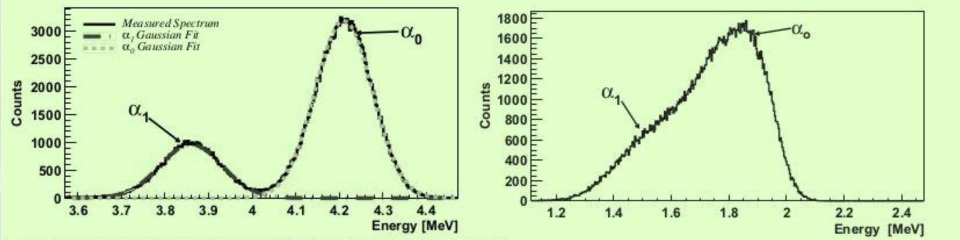
Lesson #4: We need more **nuclear** physicists.

Other catalytic nuclear fusion cycles remain to be invented hopefully allowing us to put fusion energy on the tabletop.

Muon catalysed fusion of nuclei with Z>1, D Harley et al (1990) J. Phys. G: Nucl. Part. Phys. 16 (2) p281 https://doi.org/10.1088/0954-3899/16/2/017

Nuclear physics research continues: Research towards pB fusion

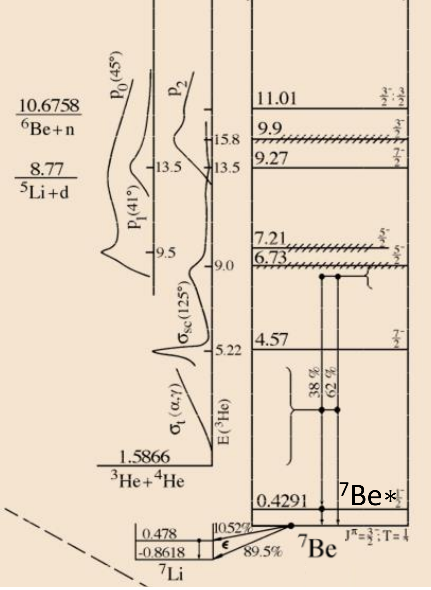
Modern nuclear data acquired 10 years ago

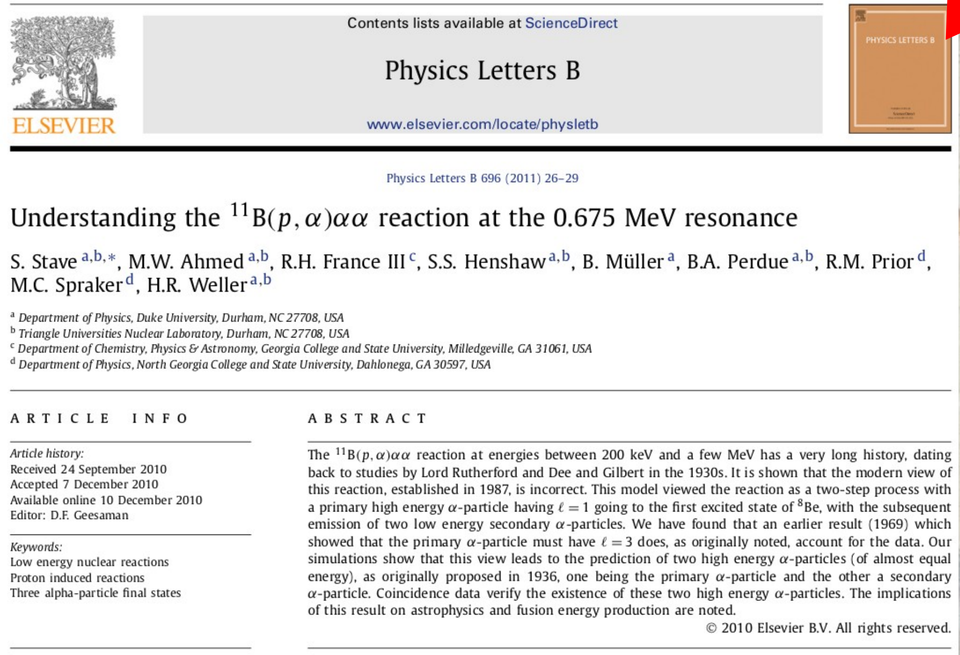


A sample spectrum taken at 30° for a 4.0 MeV proton beam. The α_0 and α_1 peaks are shown. The solid line (black) is the measured spectrum

A sample spectrum taken at 90° for 2.1 MeV proton beam. An accurate separation of α_0 from α_1 was not possible in this case.

The work continues today!




Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

ELSEVIER

Physics Letters B 696 (2011) 26–29

Understanding the $^{11}B(p,\alpha)\alpha\alpha$ reaction at the 0.675 MeV resonance

S. Stave [a,b,*], M.W. Ahmed [a,b], R.H. France III [c], S.S. Henshaw [a,b], B. Müller [a], B.A. Perdue [a,b], R.M. Prior [d], M.C. Spraker [d], H.R. Weller [a,b]

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ARTICLE INFO

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Proton induced reactions
Three alpha-particle final states

ABSTRACT

The $^{11}B(p,\alpha)\alpha\alpha$ reaction at energies between 200 keV and a few MeV has a very long history, dating back to studies by Lord Rutherford and Dee and Gilbert in the 1930s. It is shown that the modern view of this reaction, established in 1987, is incorrect. This model viewed the reaction as a two-step process with a primary high energy α-particle having $\ell = 1$ going to the first excited state of ^{8}Be, with the subsequent emission of two low energy secondary α-particles. We have found that an earlier result (1969) which showed that the primary α-particle must have $\ell = 3$ does, as originally noted, account for the data. Our simulations show that this view leads to the prediction of two high energy α-particles (of almost equal energy), as originally proposed in 1936, one being the primary α-particle and the other a secondary α-particle. Coincidence data verify the existence of these two high energy α-particles. The implications of this result on astrophysics and fusion energy production are noted.

ELSEVIER

Contents lists avai

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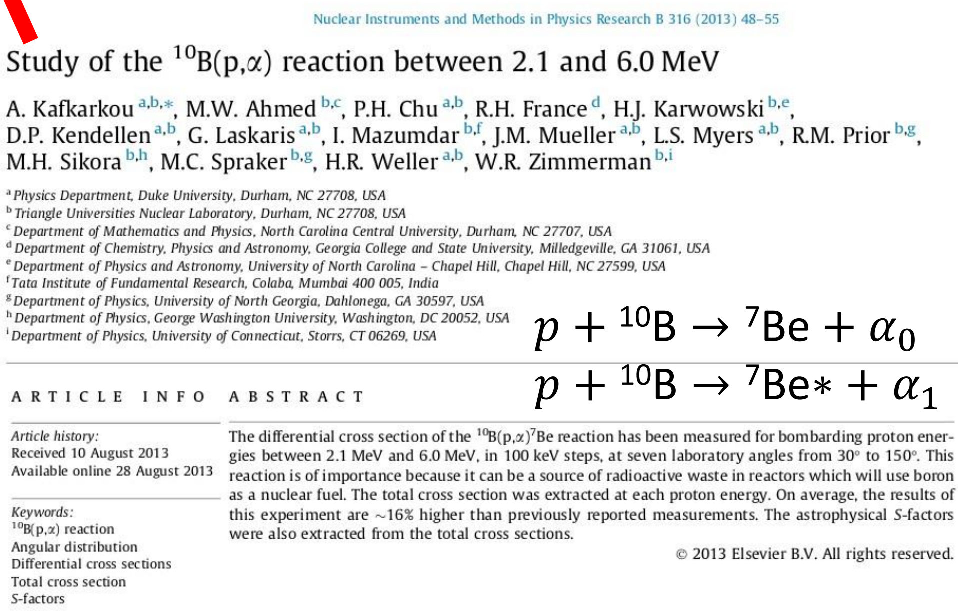
journal homepage: www


Nuclear Instruments and Methods in Physics Research B 316 (2013) 48–55

Study of the $^{10}B(p,\alpha)$ reaction between 2.1 and 6.0 MeV

A. Kafkarkou [a,b,*], M.W. Ahmed [b,c], P.H. Chu [a,b], R.H. France [d], H.J. Karwowski [b,e], D.P. Kendellen [a,b], G. Laskaris [a,b], I. Mazumdar [b,f], J.M. Mueller [a,b], L.S. Myers [a,b], R.M. Prior [b,g], M.H. Sikora [b,h], M.C. Spraker [b,g], H.R. Weller [a,b], W.R. Zimmerman [b,i]

[a] Physics Department, Duke University, Durham, NC 27708, USA
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[h] Department of Physics, George Washington University, Washington, DC 20052, USA
[i] Department of Physics, University of Connecticut, Storrs, CT 06269, USA

$$p + {}^{10}\mathrm{B} \rightarrow {}^{7}\mathrm{Be} + \alpha_0$$

$$p + {}^{10}\mathrm{B} \rightarrow {}^{7}\mathrm{Be}* + \alpha_1$$

ARTICLE INFO

Article history:
Received 10 August 2013
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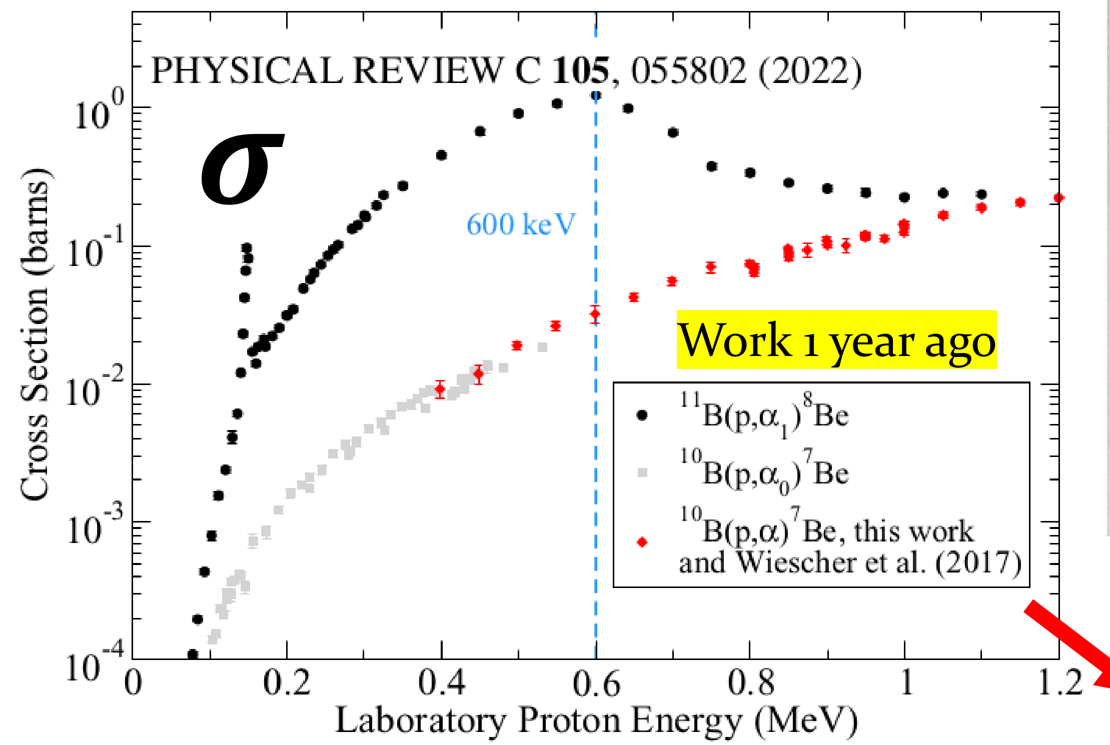
Keywords:
$^{10}B(p,\alpha)$ reaction
Angular distribution
Differential cross sections
Total cross section
S-factors

ABSTRACT

The differential cross section of the $^{10}B(p,\alpha)^7Be$ reaction has been measured for bombarding proton energies between 2.1 MeV and 6.0 MeV, in 100 keV steps, at seven laboratory angles from 30° to 150°. This reaction is of importance because it can be a source of radioactive waste in reactors which will use boron as a nuclear fuel. The total cross section was extracted at each proton energy. On average, the results of this experiment are ~16% higher than previously reported measurements. The astrophysical S-factors were also extracted from the total cross sections.

S-factor helps isolate the impact of tunneling



PHYSICAL REVIEW C **105**, 055802 (2022)

σ

600 keV

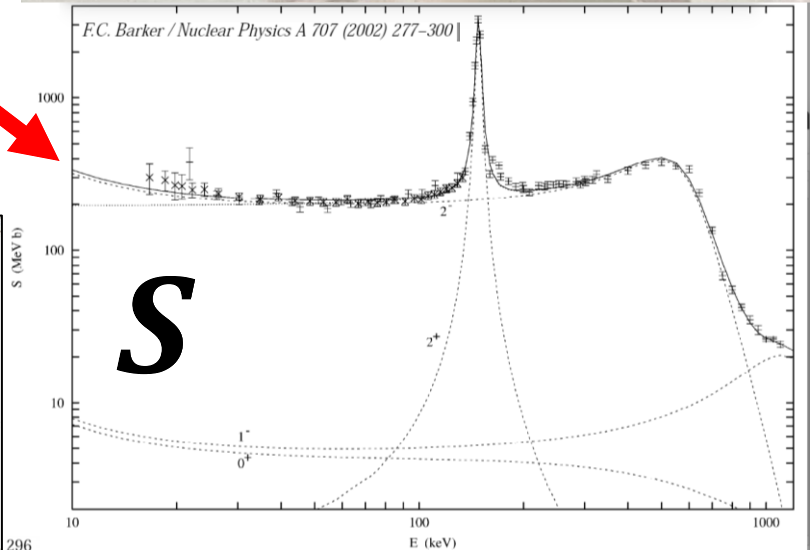
Work 1 year ago

S-Factor:

$$S(E) = E e^{2\pi\eta} \sigma(E)$$

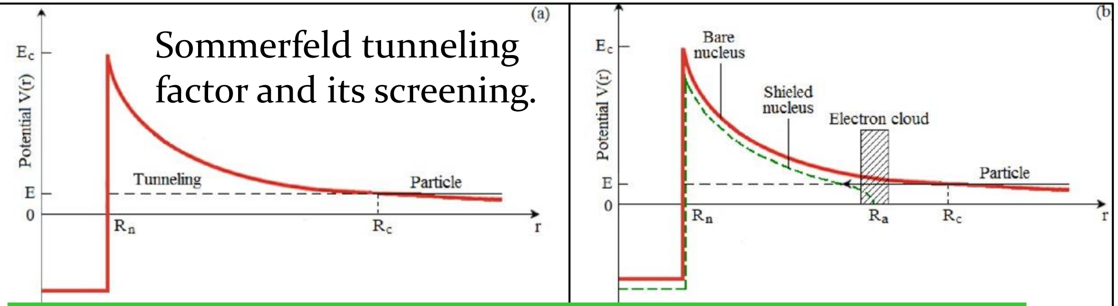
Sommerfeld tunneling factor:

$$\eta = \frac{Z_1 Z_2 e^2}{4\pi\epsilon_0 \hbar v} = \frac{Z_1 Z_2 \alpha}{\beta}$$



F.C. Barker / Nuclear Physics A 707 (2002) 277–300

S



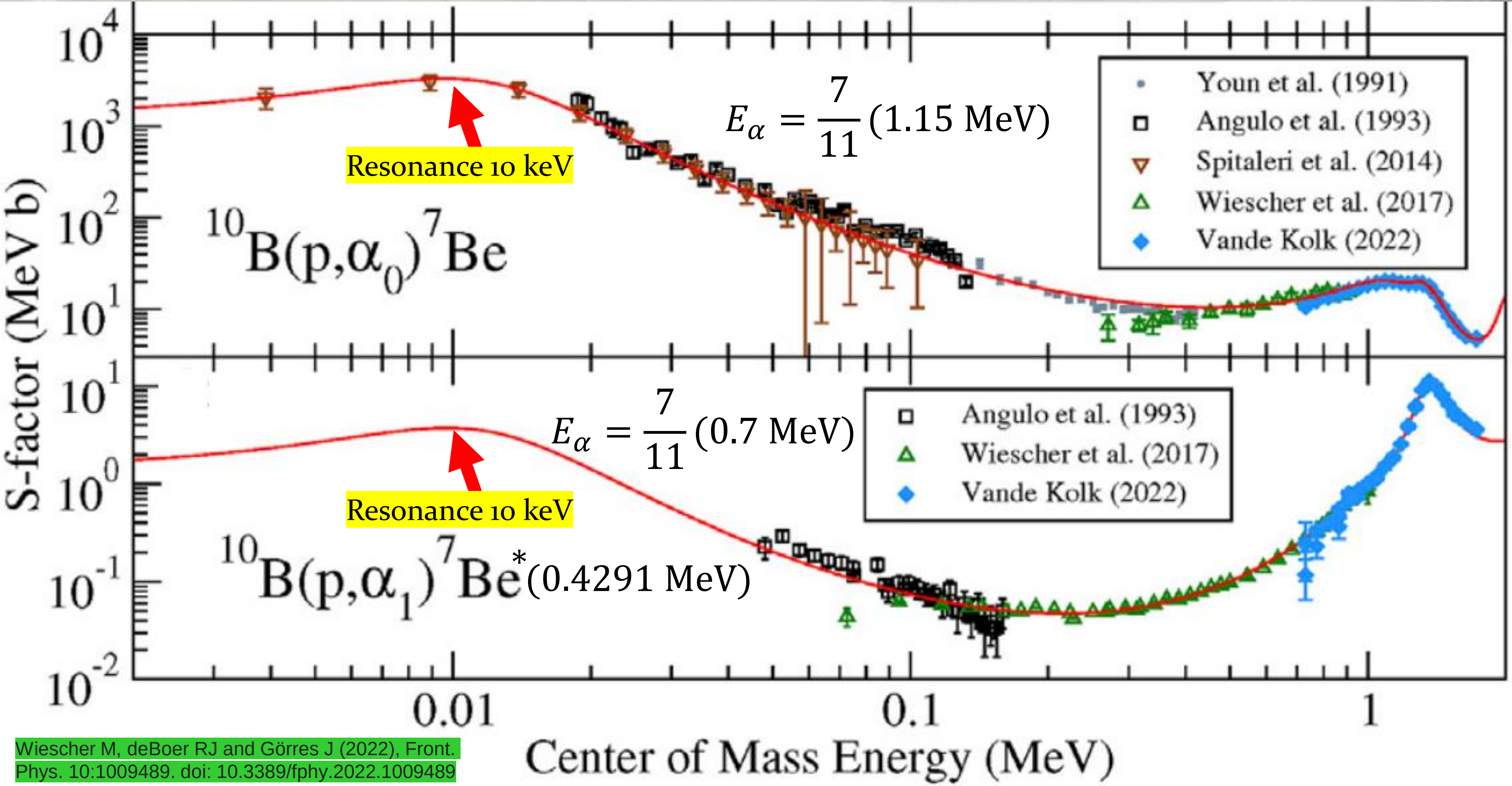
Sommerfeld tunneling factor and its screening.

Cvetinović, Aleksandra. *Doctoral Thesis*. Diss. Univerza v Ljubljani, Fakulteta za matematiko in fiziko, 2015.

The status of $p + {}^{10}_{5}B$ today

The signature of light element fusion is high energy α production.

This is the lowest resonance of them all at 10 keV.



Resonance 10 keV

$$E_\alpha = \frac{7}{11}(1.15\text{ MeV})$$

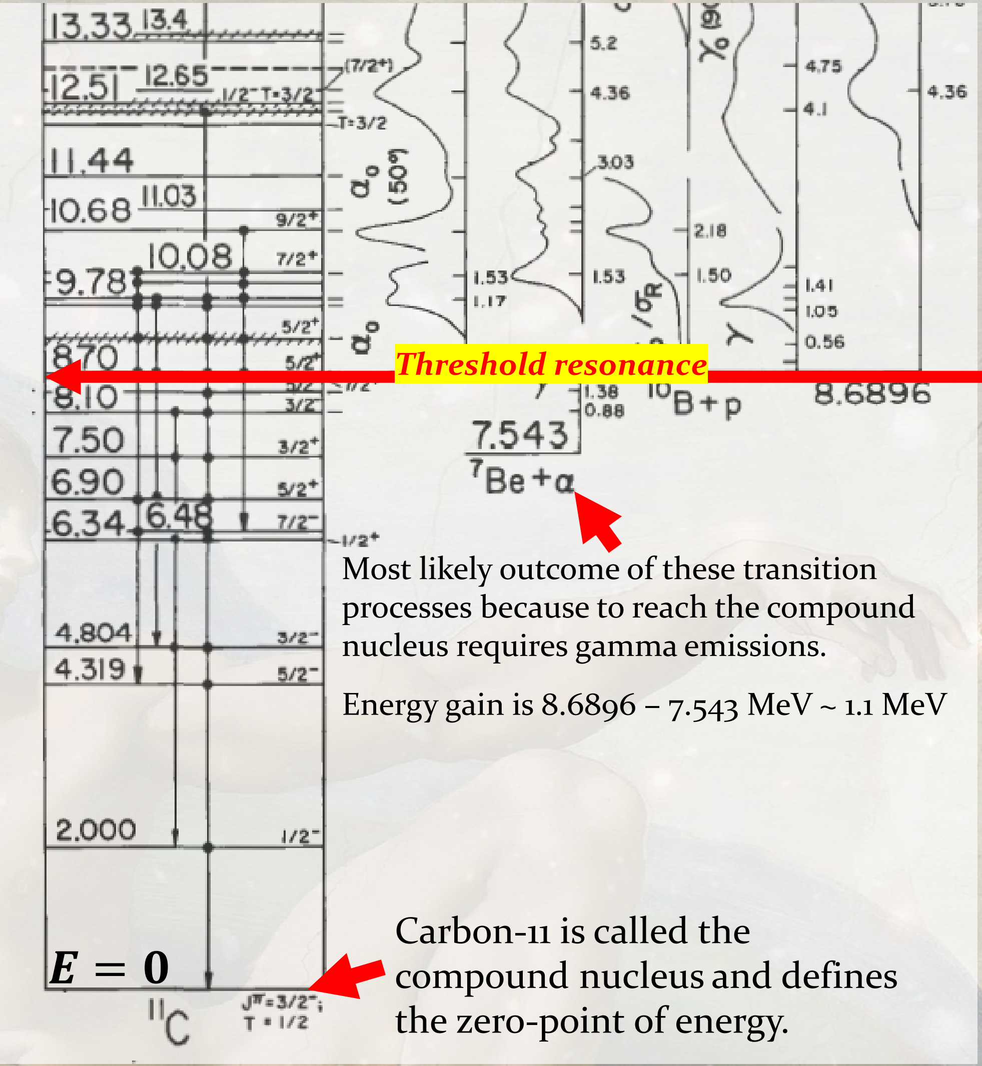
Resonance 10 keV

$$E_\alpha = \frac{7}{11}(0.7\text{ MeV})$$

(0.4291 MeV)

Wiescher M, deBoer RJ and Görres J (2022), Front. Phys. 10:1009489. doi: 10.3389/fphy.2022.1009489

Explanation of resonance transmutation of $p + {}^{10}_{5}B \rightarrow {}^{7}_{4}Be + \alpha + (1.15\ \text{MeV})$



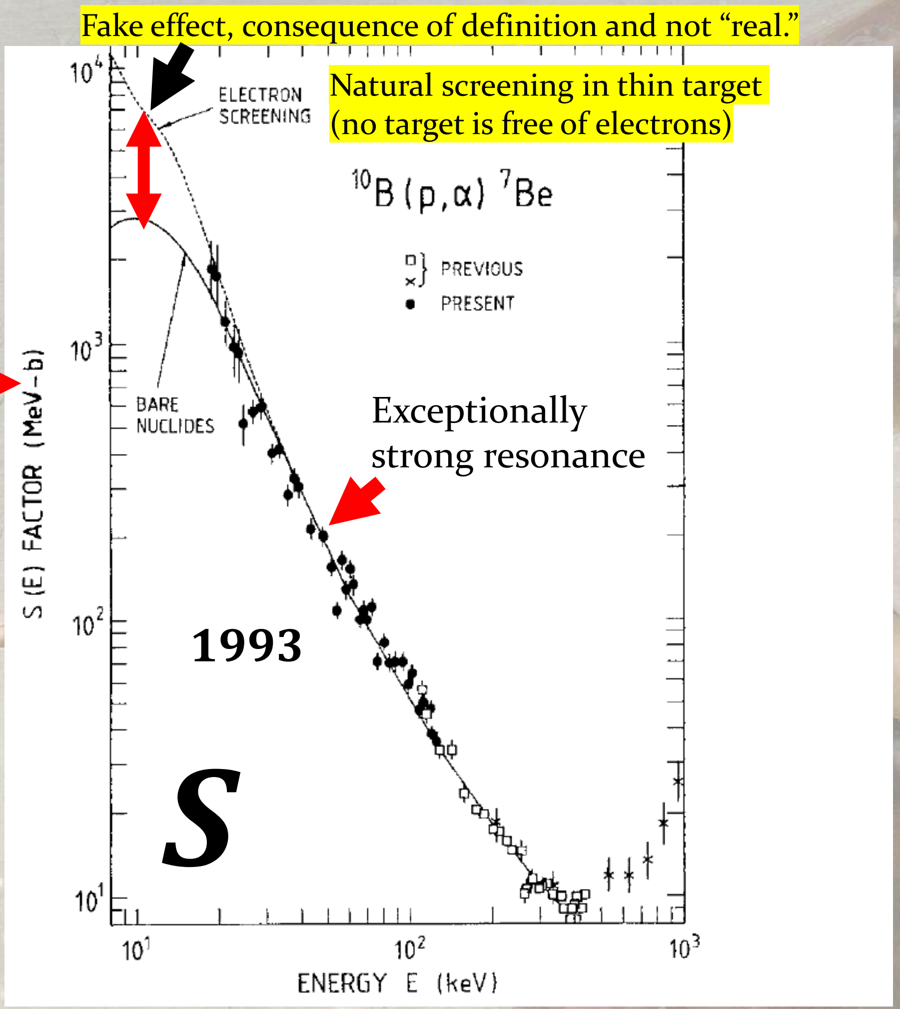
Threshold resonance

Most likely outcome of these transition processes because to reach the compound nucleus requires gamma emissions.

Energy gain is 8.6896 – 7.543 MeV ~ 1.1 MeV

Carbon-11 is called the compound nucleus and defines the zero-point of energy.

$\boldsymbol{E = 0}$



Fake effect, consequence of definition and not "real."

Natural screening in thin target (no target is free of electrons)

Exceptionally strong resonance

1993

S

From JR lecture at Duke University May 7, 2013

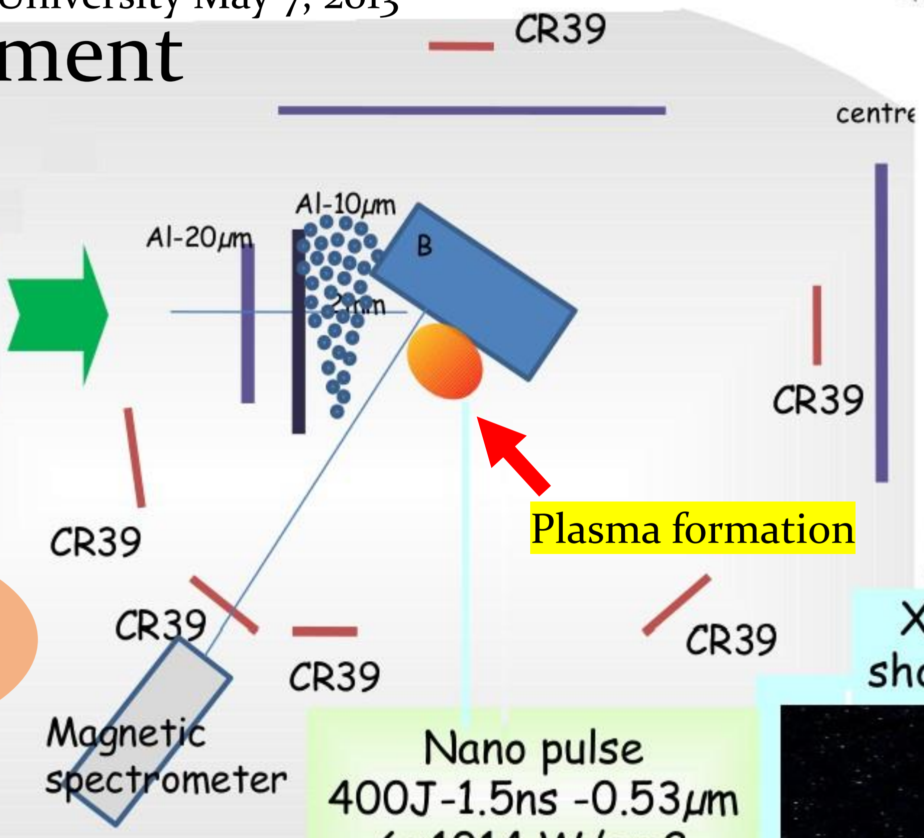
LULI Experiment

Pico pulse accelerates protons

Pico pulse
20J-1ps-0.53µm
6x1018 W/cm2

Proton beam formation

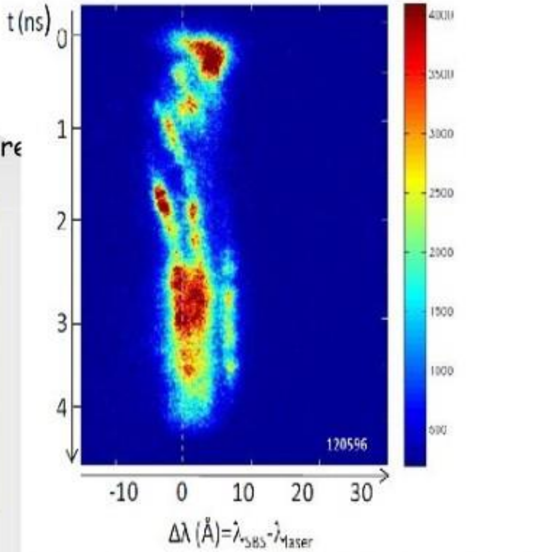
Exploration of $p\,{}^{11}_{5}B$ fusion



Plasma formation

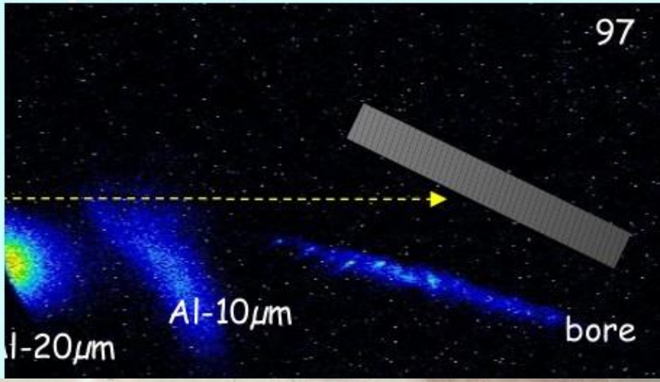
Nano pulse
400J-1.5ns -0.53µm
6x1014 W/cm2

Nano pulse, 400J produces the B plasma



Time-resolved spectrum of stimulated Brillouin backscattering (SBS) of the nanosecond pulse collected in the backward direction.

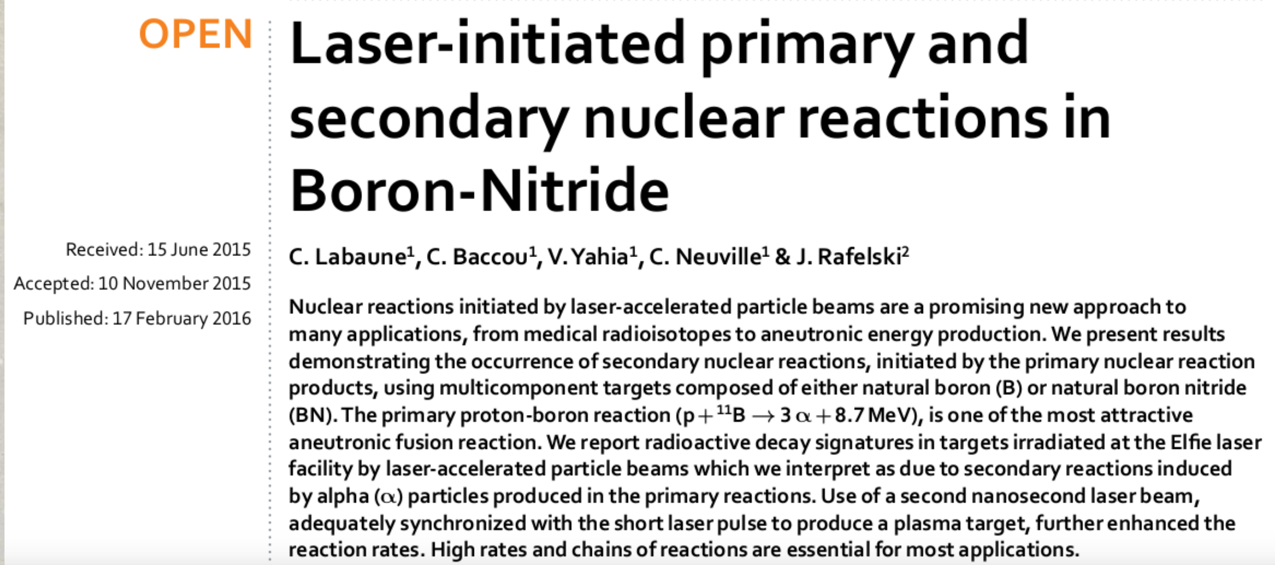
X-ray pinhole image showing the 3 plasmas



Labaune, C., et al. "Fusion reactions initiated by laser-accelerated particle beams in a laser-produced plasma." *Nature Communications* 4.1 (2013): 2506.

First exploration of boron-nitride **BN** catalytic cycle

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.



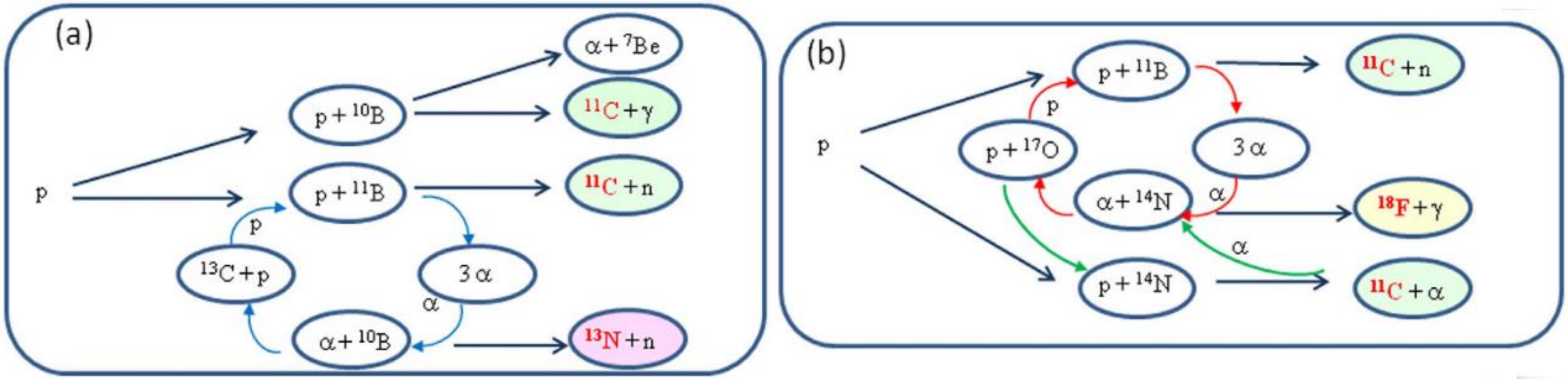
OPEN

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

Received: 15 June 2015
Accepted: 10 November 2015
Published: 17 February 2016

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.

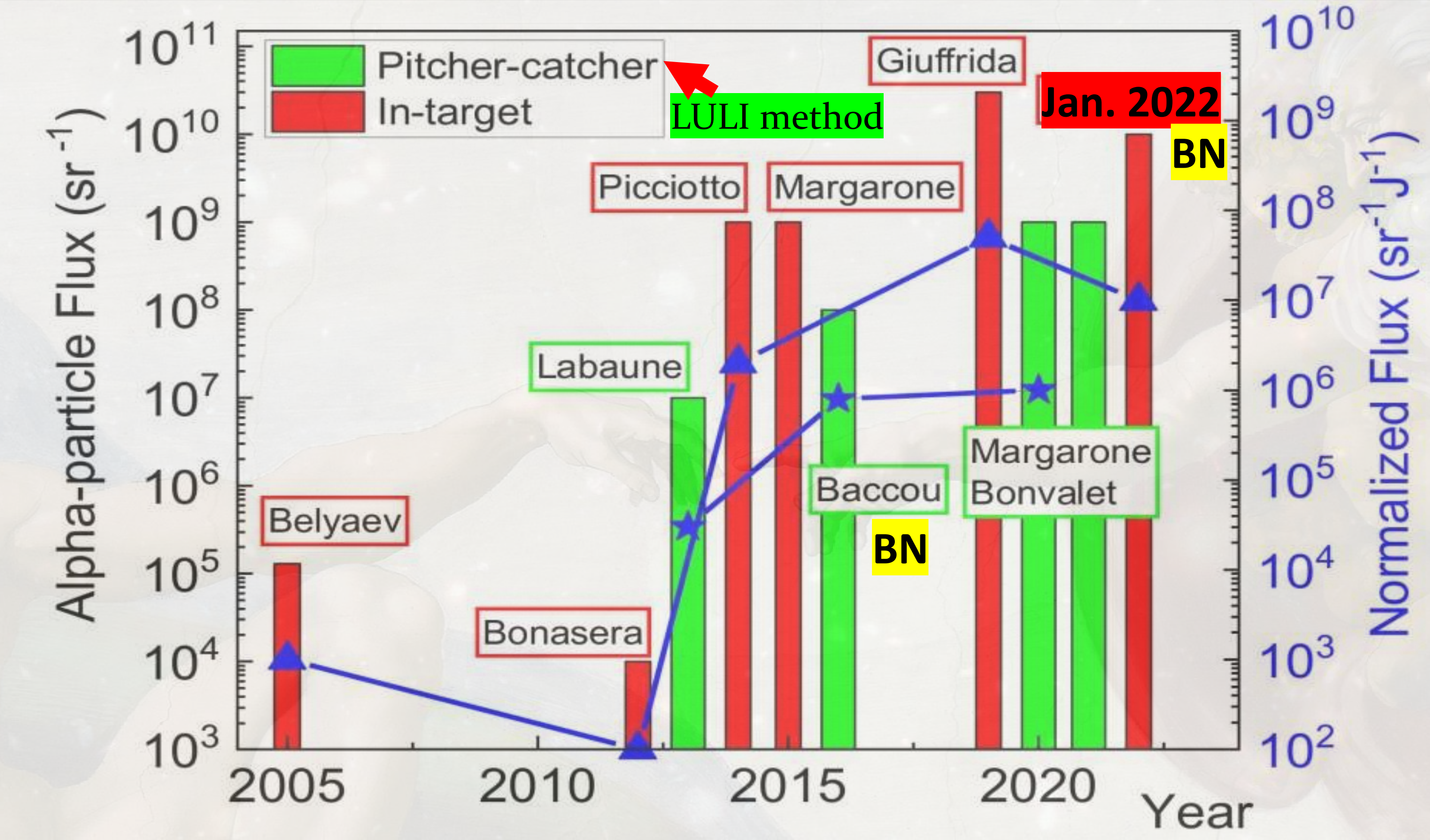


Scheme of the primary and secondary nuclear reactions produced by the interaction between a laser-accelerated proton beam and (**a**) a natural boron target, (**b**) a boron-nitride target. In the case of the BN targets the reactions with ${}^{10}B$ can also occur but are not shown for clarity.

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

Laser Contrast Ratio: $R = \dfrac{Pulse\ Intensity}{Prepulse/pedestal\ Intenity}$

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



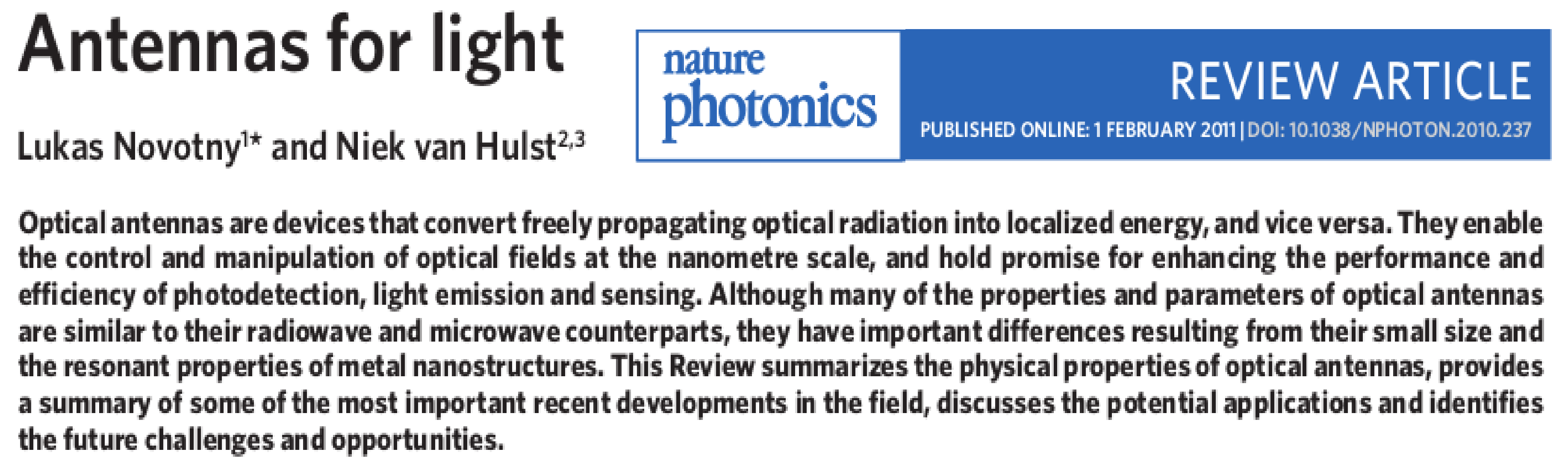
LULI method

Jan. 2022

BN

BN

Plasmonic fusion



Antennas for light

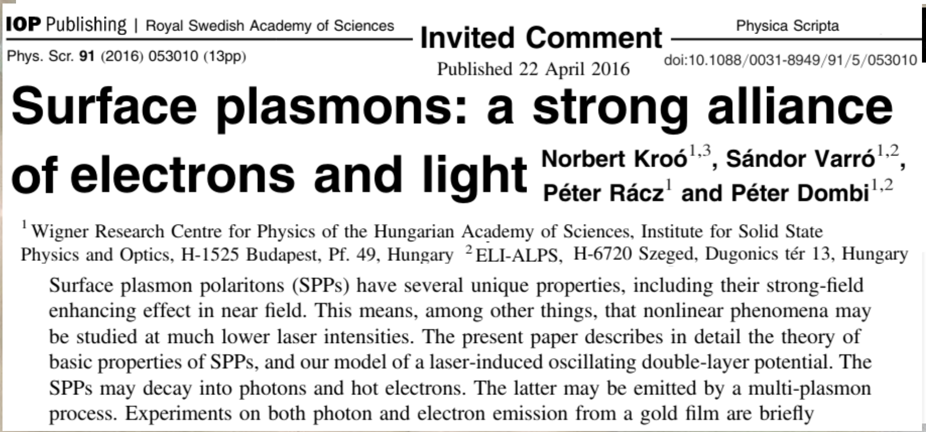
Lukas Novotny[1*] and Niek van Hulst[2,3]

nature photonics

REVIEW ARTICLE

PUBLISHED ONLINE: 1 FEBRUARY 2011 | DOI: 10.1038/NPHOTON.2010.237

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.



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Physica Scripta

Phys. Scr. **91** (2016) 053010 (13pp)

Invited Comment

doi:10.1088/0031-8949/91/5/053010

Published 22 April 2016

Surface plasmons: a strong alliance of electrons and light

Norbert Kroó[1,3], Sándor Varró[1,2], Péter Rácz[1] and Péter Dombi[1,2]

[1] Wigner Research Centre for Physics of the Hungarian Academy of Sciences, Institute for Solid State Physics and Optics, H-1525 Budapest, Pf. 49, Hungary [2] ELI-ALPS, H-6720 Szeged, Dugonics tér 13, Hungary

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

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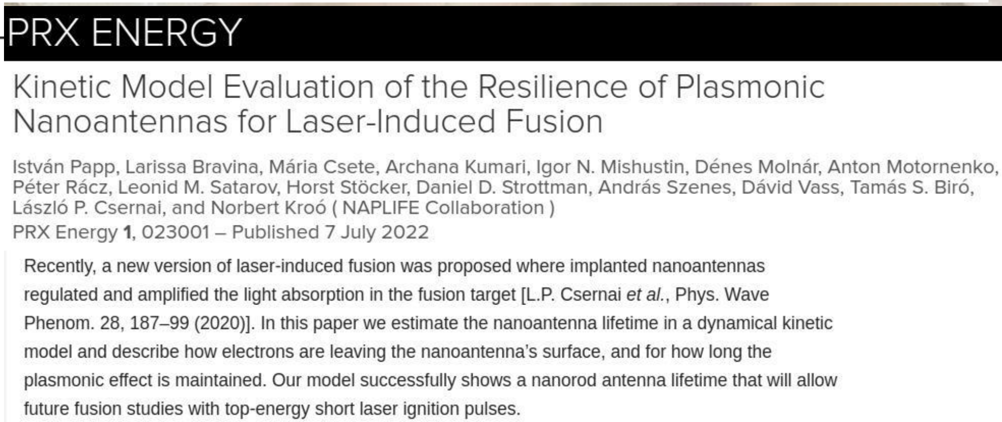


PRX ENERGY

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

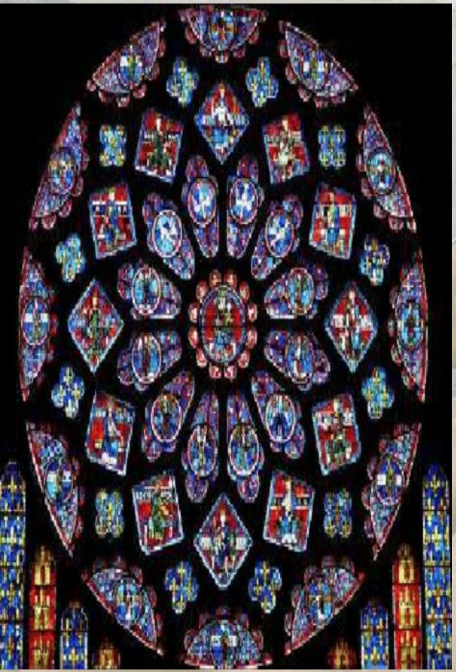
István Papp, Larissa Bravina, Mária Csete, Archana Kumari, Igor N. Mishustin, Dénes Molnár, Anton Motornenko, Péter Rácz, Leonid M. Satarov, Horst Stöcker, Daniel D. Strottman, András Szenes, Dávid Vass, Tamás S. Biró, László P. Csernai, and Norbert Kroó (NAPLIFE Collaboration)

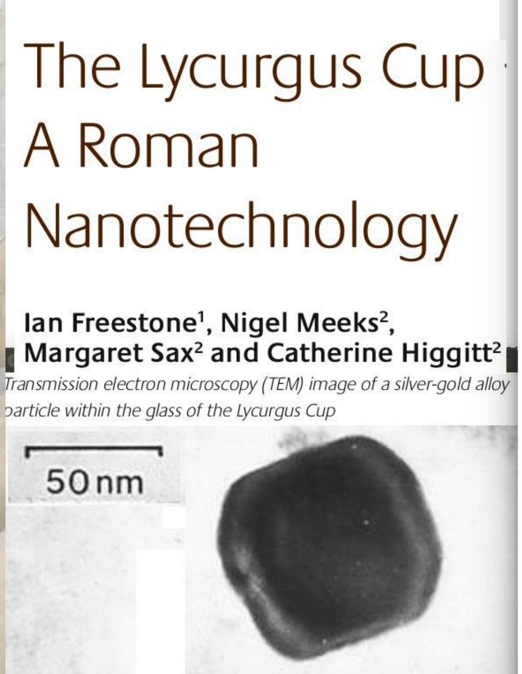
PRX Energy **1**, 023001 – Published 7 July 2022

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.

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).**

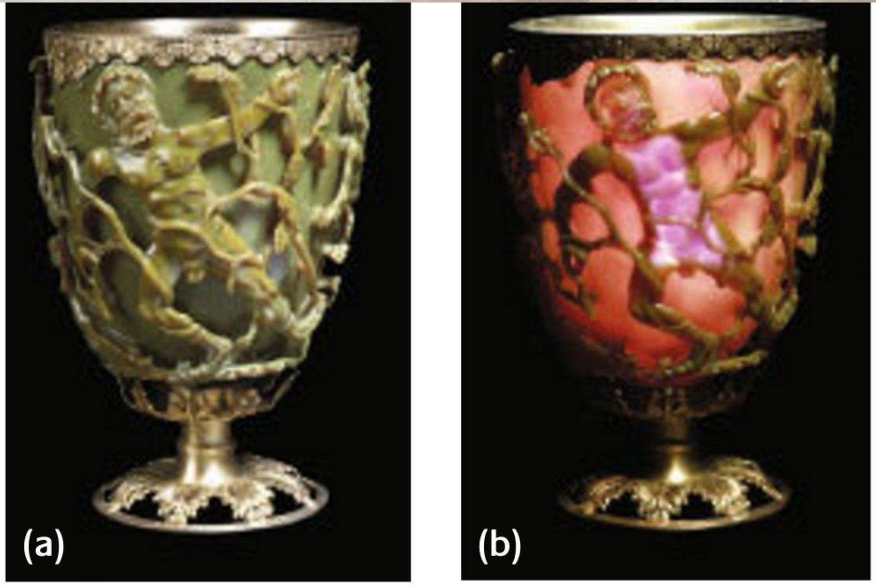




The Lycurgus Cup
A Roman
Nanotechnology

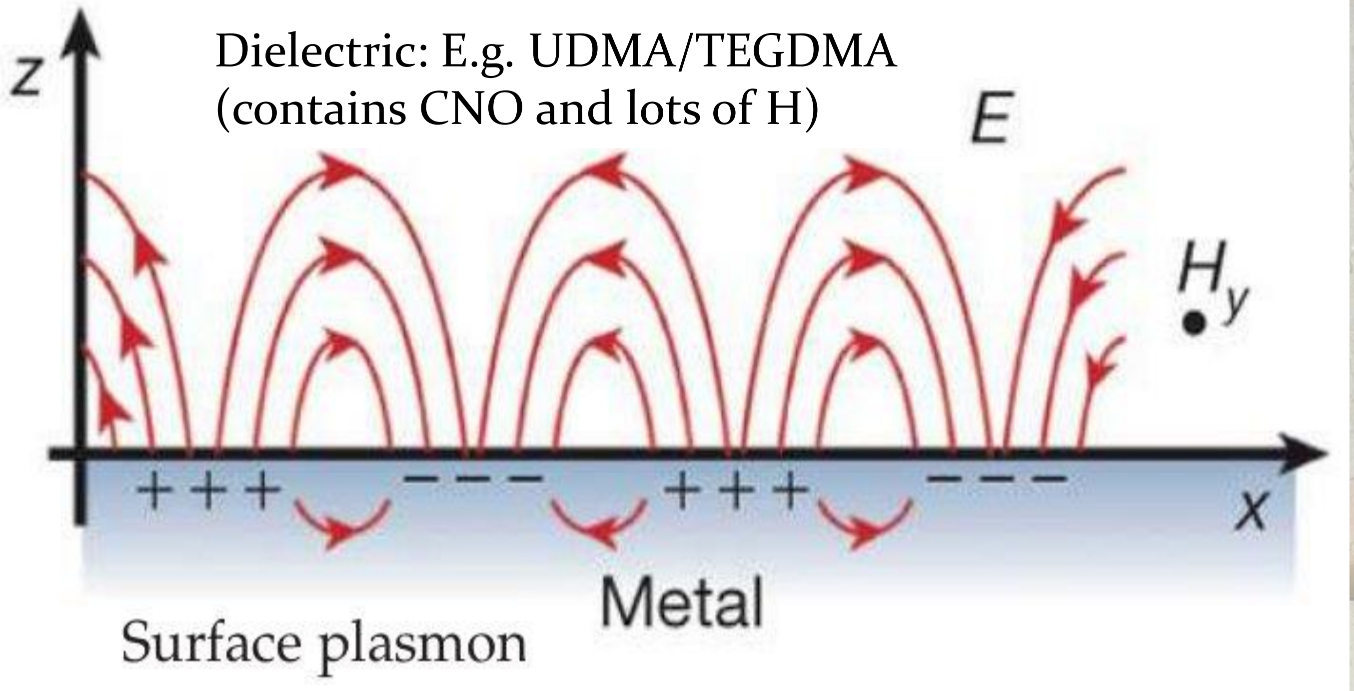
Ian Freestone[1], Nigel Meeks[2],
Margaret Sax[2] and Catherine Higgitt[2]

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



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

A new beginning: Coherent light antenna response: Surface electro-magnetic fields 1000-fold (in numerical model) amplified



Dielectric: E.g. UDMA/TEGDMA
(contains CNO and lots of H)

Surface plasmon

Plasmons are **coherent excitations** which requires sub-picosecond laser pulses.

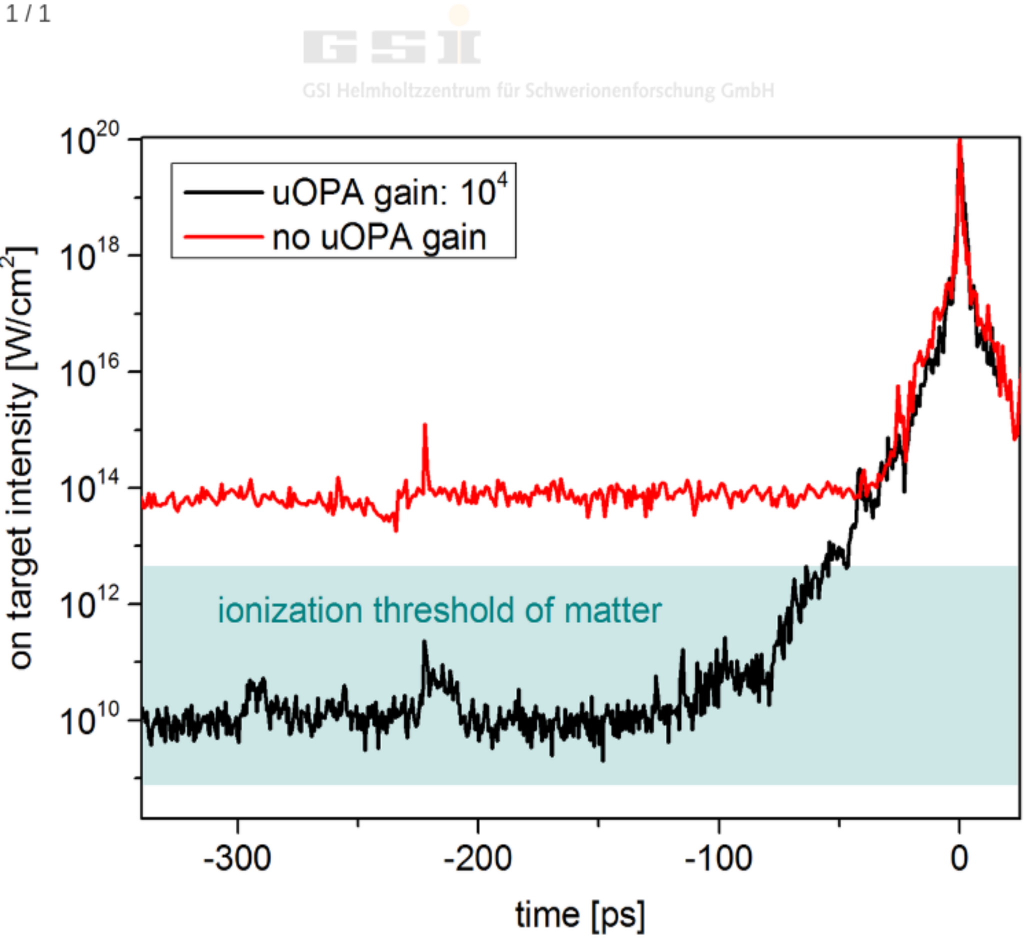
Laser energy is focused to sub-diffraction limit by nano-antennas.

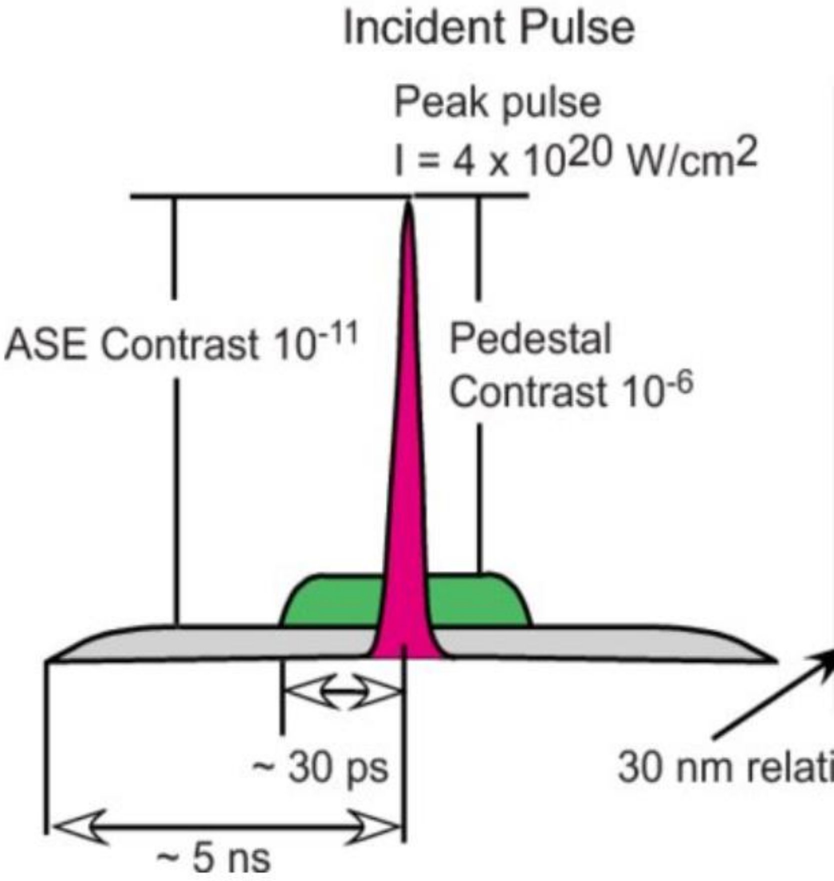
Nanoparticles act as resonant antennas working at a fraction of the incident light‘s wavelength.

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

Definition of plasmonic fusion: **Commercially available femto-sec 10’s of mJ high contrast lasers excite surface plasmons in dielectrics which accelerate protons to 100’s of keV energies.** Screening of electrons and acceleration of protons to fascilitate fusion processes. See lectures by: **Norbert Kroó, Laszlo Csernai, Tamas Biro, and Istvan Papp**

Light antenna energy concentration helps reduce contrast requirement



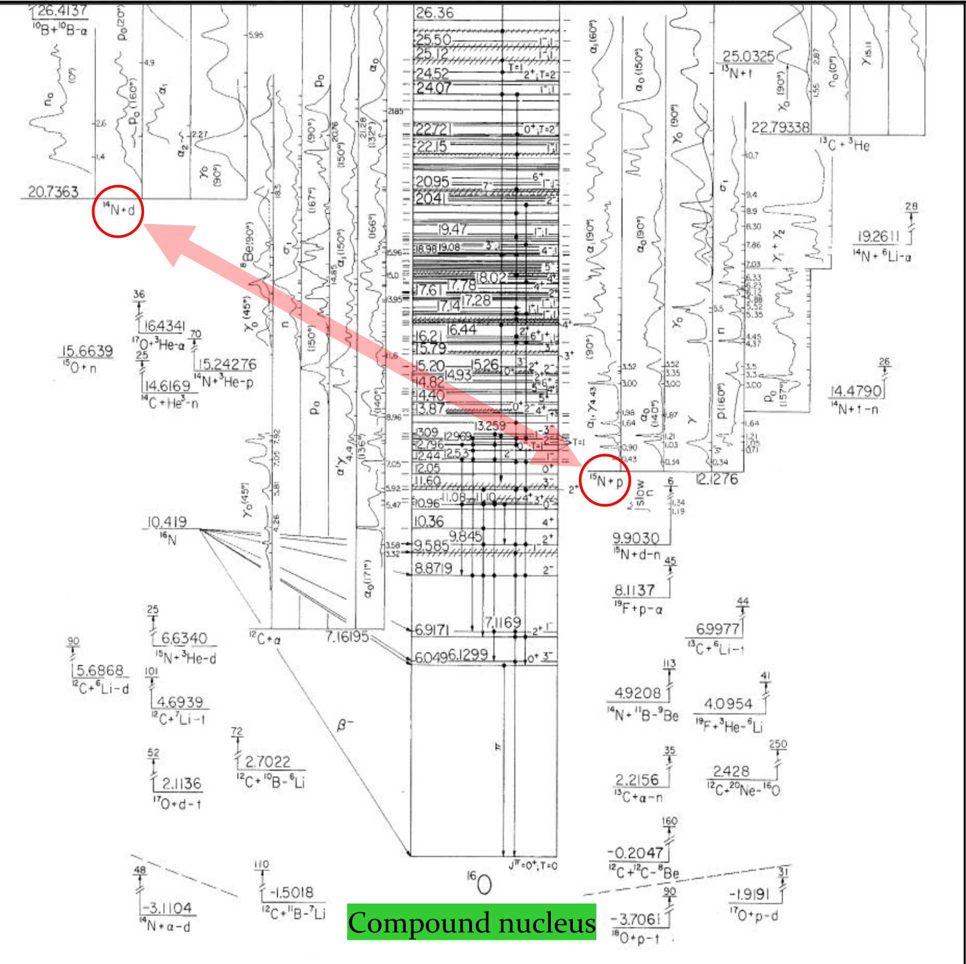


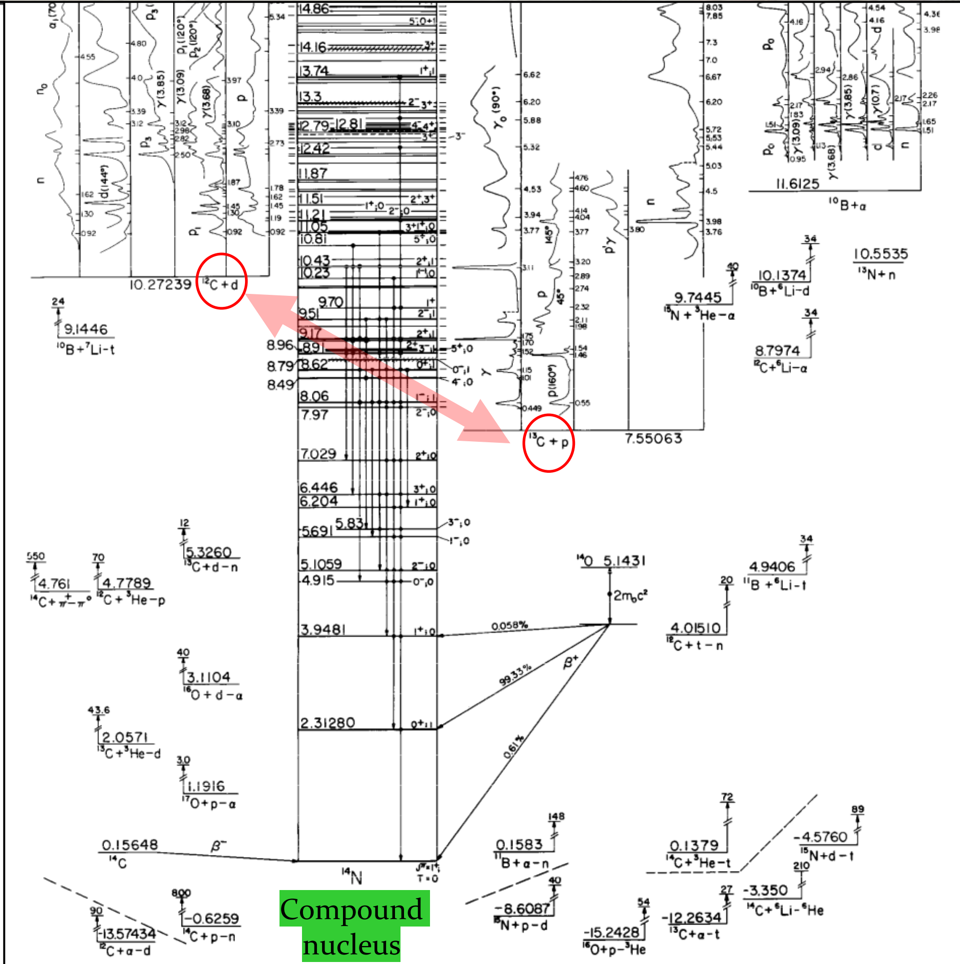
Remarks about plasmonic fusion: It’s hard to make deuterons in UDMA/TEGDMA

All reactions to generate deuteron are strongly endothermic for example:

$p + {}^{15}N \rightarrow d + {}^{14}N + (-8.5\text{ MeV})$

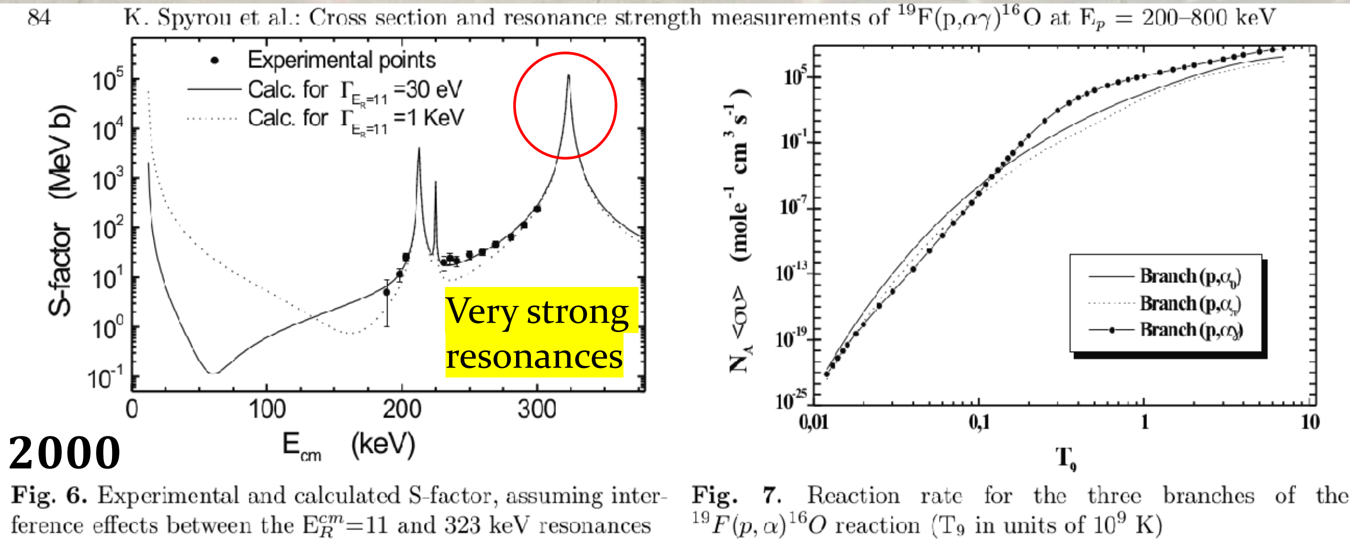
$p + {}^{13}C \rightarrow d + {}^{12}C + (-2.7\text{ MeV})$





Beyond boron, another plasmonic opportunity:

Fluorine ${}^{19}_{9}F$ has many resonances to explore



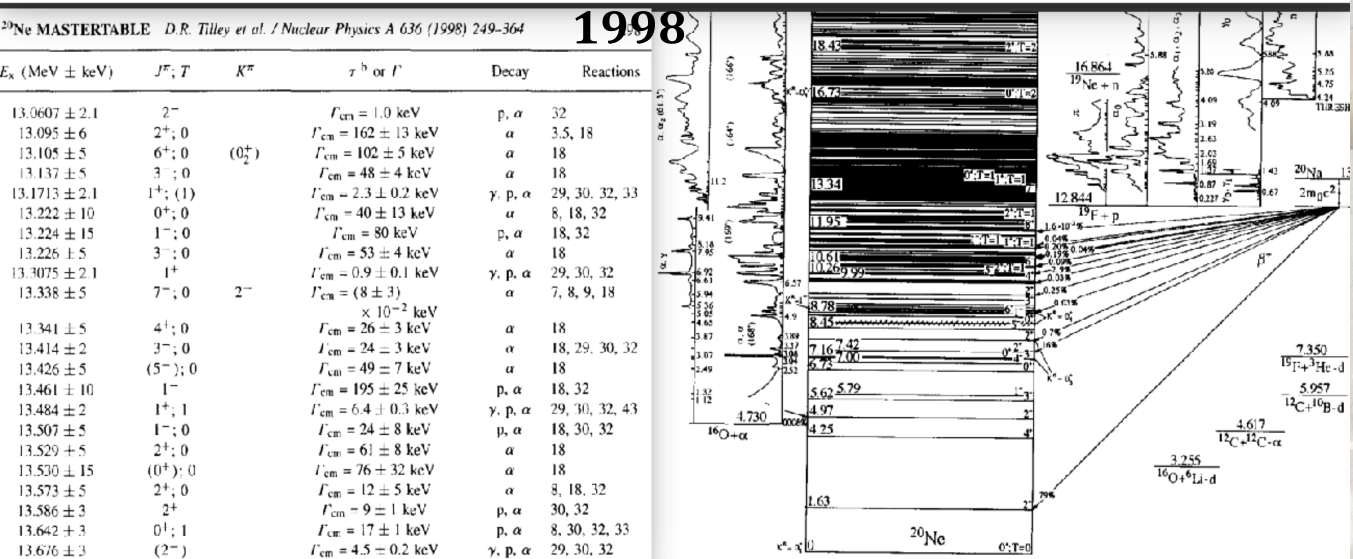
84 K. Spyrou et al.: Cross section and resonance strength measurements of ${}^{19}F(p,\alpha\gamma){}^{16}O$ at E_p = 200–800 keV

Very strong resonances

2000

Fig. 6. Experimental and calculated S-factor, assuming interference effects between the E_R^{cm}=11 and 323 keV resonances

Fig. 7. Reaction rate for the three branches of the ${}^{19}F(p,\alpha){}^{16}O$ reaction (T_9 in units of 10^9 K)



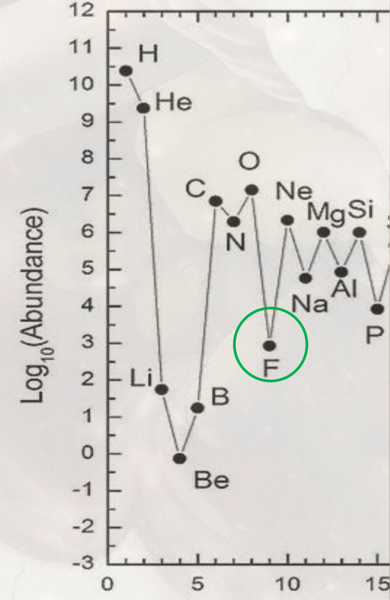
1998

^{20}Ne MASTERTABLE *D.R. Tilley et al. / Nuclear Physics A 636 (1998) 249–364*

E_x (MeV ± keV)	J^π; T	K^π	τ ^{b} or Γ	Decay	Reactions
13.0607 ± 2.1	2^-		Γ_{cm} = 1.0 keV	p, α	32
13.095 ± 6	2^+; 0		Γ_{cm} = 162 ± 13 keV	α	3.5, 18
13.105 ± 5	6^+; 0	(0_2^+)	Γ_{cm} = 102 ± 5 keV	α	18
13.137 ± 5	3^-; 0		Γ_{cm} = 48 ± 4 keV	α	18
13.1713 ± 2.1	1^+; (1)		Γ_{cm} = 2.3 ± 0.2 keV	γ, p, α	29, 30, 32, 33
13.222 ± 10	0^+; 0		Γ_{cm} = 40 ± 13 keV	α	8, 18, 32
13.224 ± 15	1^-; 0		Γ_{cm} = 80 keV	p, α	18, 32
13.226 ± 5	3^-; 0		Γ_{cm} = 53 ± 4 keV	α	18
13.3075 ± 2.1	1^+		Γ_{cm} = 0.9 ± 0.1 keV	γ, p, α	29, 30, 32
13.338 ± 5	7^-; 0	2^-	Γ_{cm} = (8 ± 3) × 10^{-2} keV	α	7, 8, 9, 18
13.341 ± 5	4^+; 0		Γ_{cm} = 26 ± 3 keV	α	18
13.414 ± 2	3^-; 0		Γ_{cm} = 24 ± 3 keV	α	18, 29, 30, 32
13.426 ± 5	(5^-); 0		Γ_{cm} = 49 ± 7 keV	α	18
13.461 ± 10	1^-		Γ_{cm} = 195 ± 25 keV	p, α	18, 32
13.484 ± 2	1^+; 1		Γ_{cm} = 6.4 ± 0.3 keV	γ, p, α	29, 30, 32, 43
13.507 ± 5	1^-; 0		Γ_{cm} = 24 ± 8 keV	p, α	18, 30, 32
13.529 ± 5	2^+; 0		Γ_{cm} = 61 ± 8 keV	α	18
13.530 ± 15	(0^+); 0		Γ_{cm} = 76 ± 32 keV	α	18
13.573 ± 5	2^+; 0		Γ_{cm} = 12 ± 5 keV	α	8, 18, 32
13.586 ± 3	2^+		Γ_{cm} = 9 ± 1 keV	p, α	30, 32
13.642 ± 3	0^+; 1		Γ_{cm} = 17 ± 1 keV	p, α	8, 30, 32, 33
13.676 ± 3	(2^-)		Γ_{cm} = 4.5 ± 0.2 keV	γ, p, α	29, 30, 32

Highly active mono-isotope element due to the extra neutron.

Nuclear chemistry quickly becomes very complicated! Even among the lighter elements, the number of possible reactions can be large.



The real future of civilian nuclear fusion

Loose ideas for a proposal to create a future fusion program

Searching to implement fusion, we need:

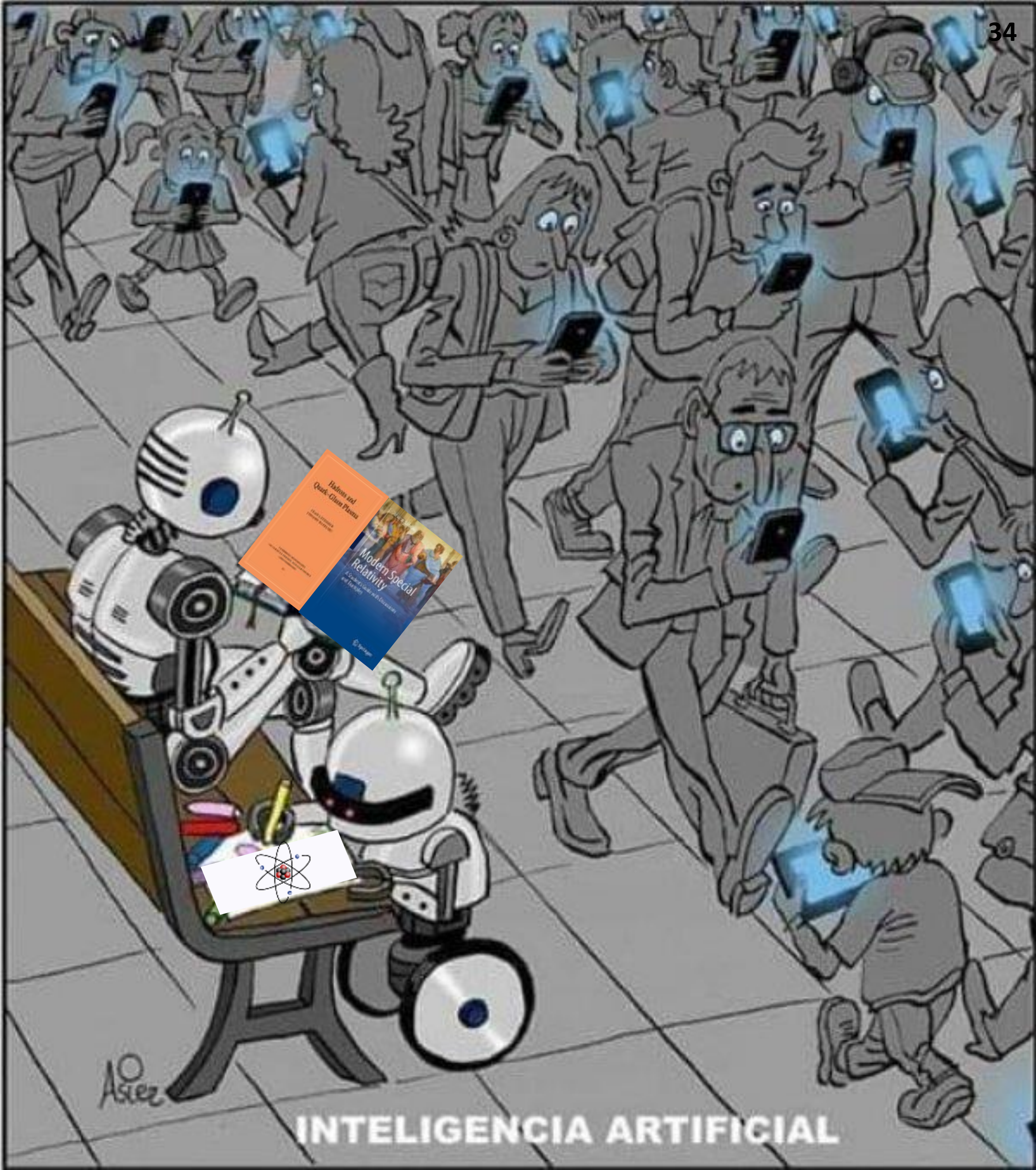
1. An abundant fuel (anything but tritium)
2. **High contrast lasers:** A non-equilibrium **aneutronic** process
3. **Plasmonics:** Enhances nuclear fusion reaction environ (coherence & screening)
4. **Nuclear physics:** Identify/invent the right (catalytic) nuclear fusion cycle

We have to encourage interdisciplinary research into novel nuclear fusion synergies between strong fields, plasma properties, nuclear theory,& plasmonics.

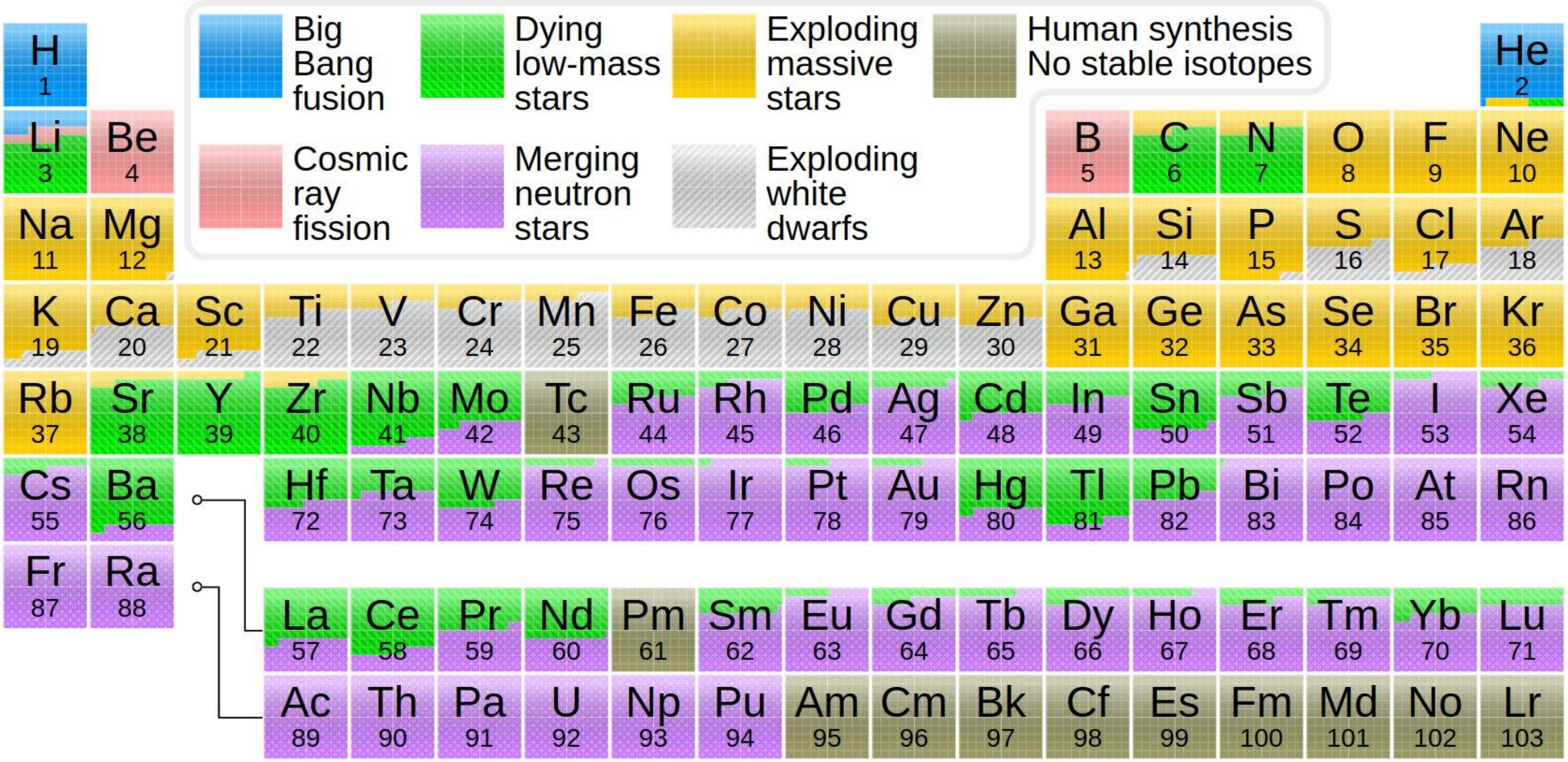
I thank **Andrew Steinmetz** for interest in, and kind assistance with preparation of this talk.

Thank you for your attention!

Johann Rafelski



Appendix A: A very optimistic knowledge based view about the origin of elements

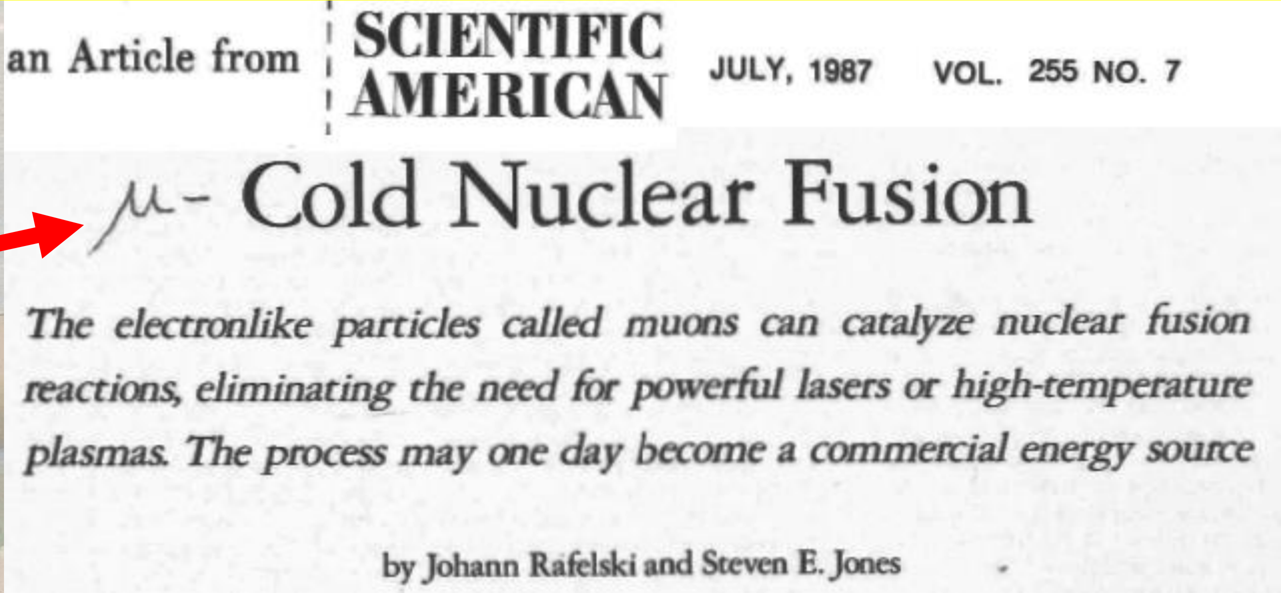


Johnson, J. A. "Populating the periodic table: Nucleosynthesis of the elements." *Science* 363.6426 (2019): 474-478.

Appendix B: 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

μ- 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

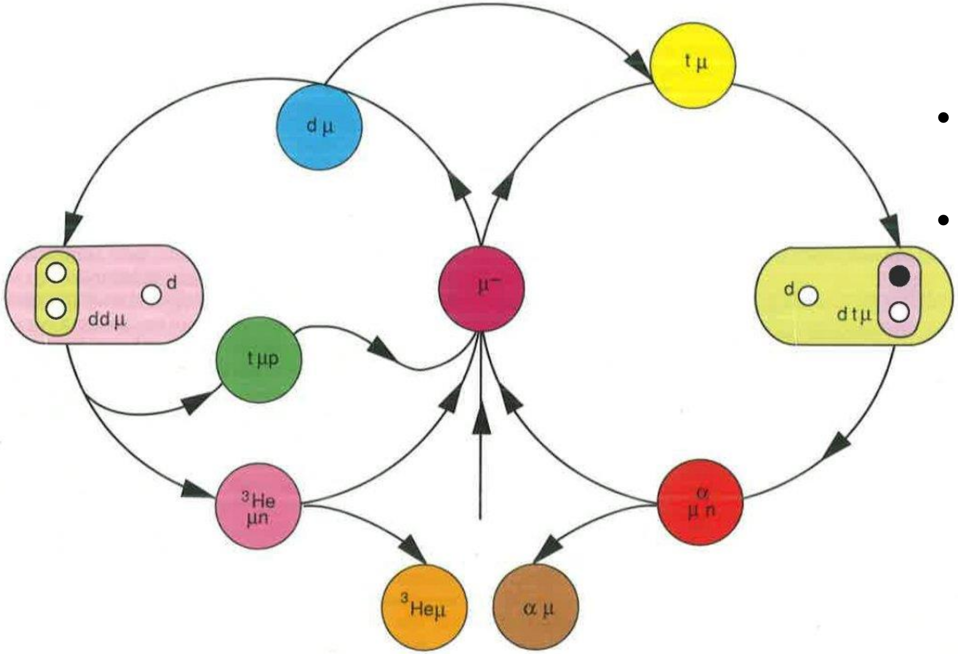
by Johann Rafelski and Steven E. Jones

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

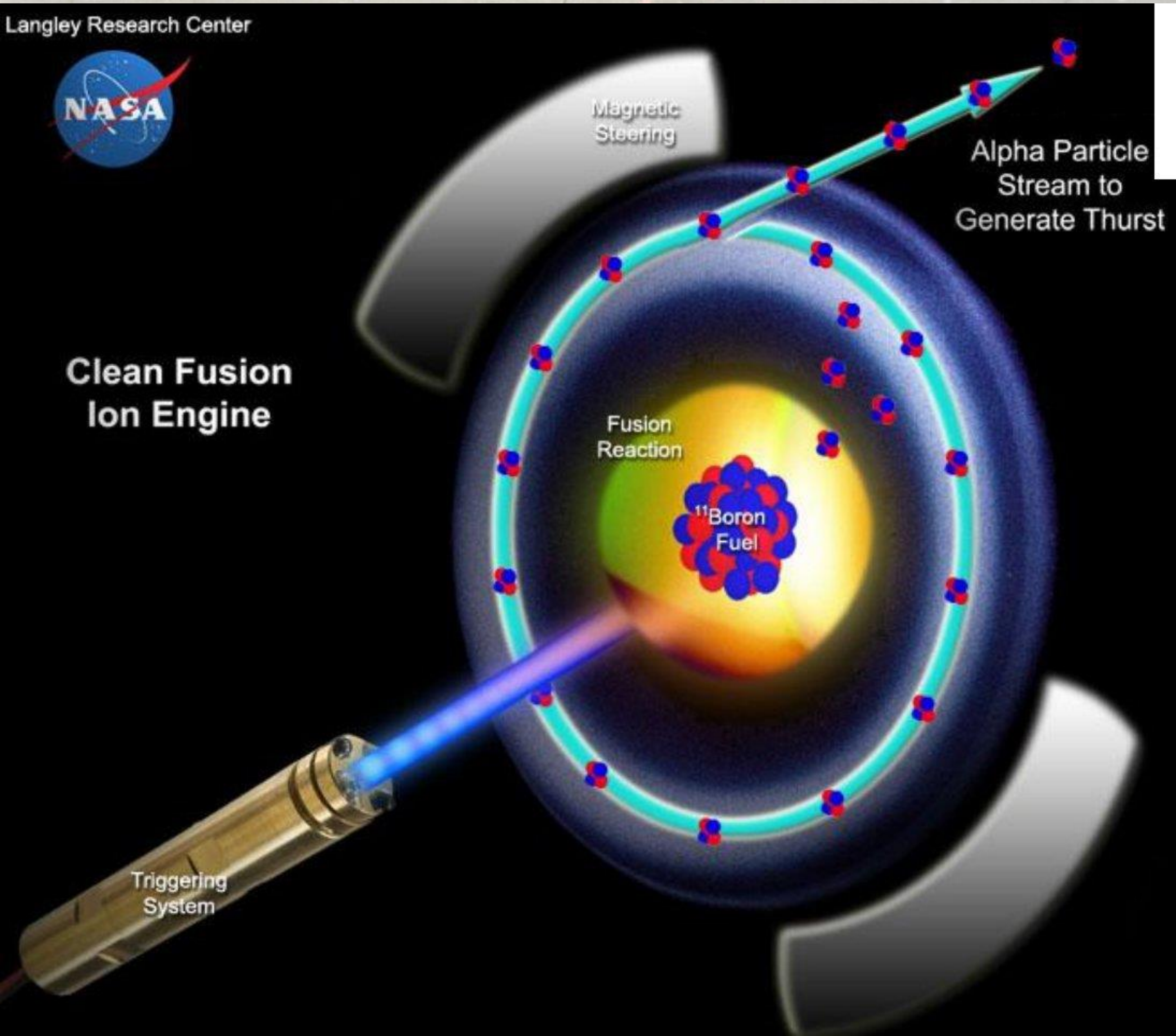
Representation of the cycle of $dt\mu$ MuCF fusion processes.



- 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.

Appendix C: Fusion in space travel




Advanced Fusion Reactors for Space Propulsion and Power Systems
11pBNASA_ICOPSPresentation.pdf

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

Appendix D: Two-laser pB process

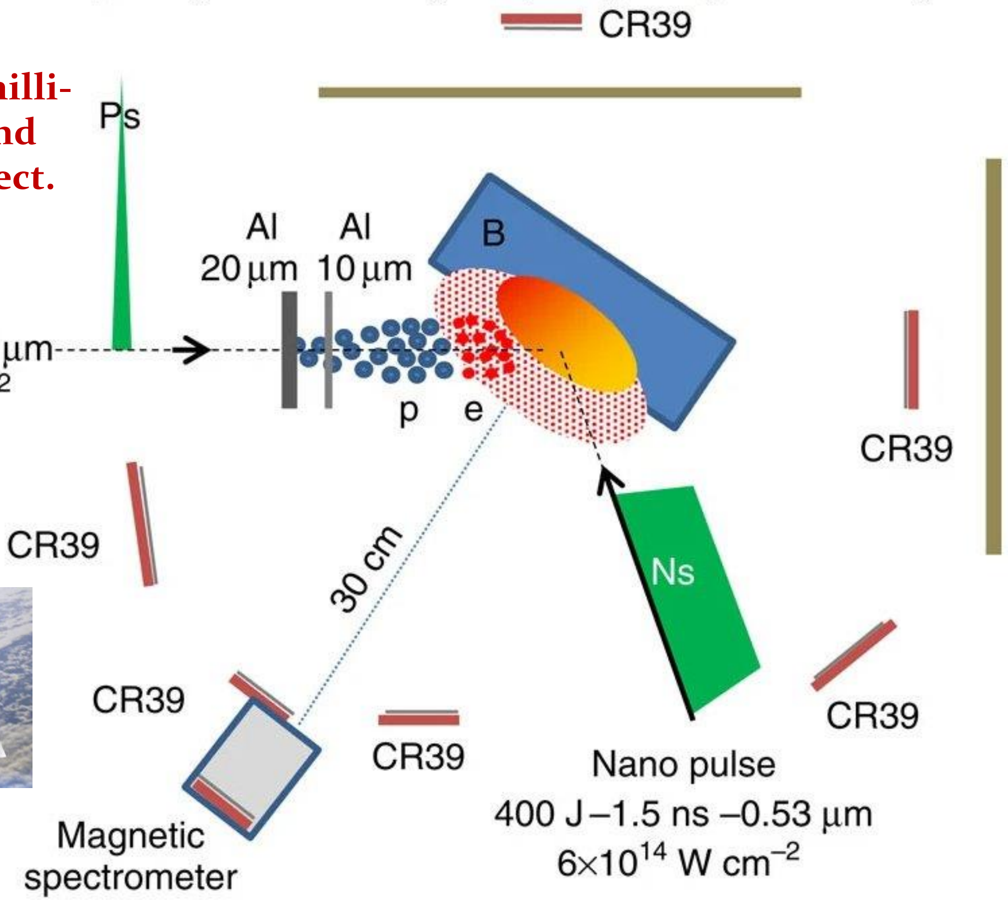
The long-pulsed nano-laser produces plasma and sweeps electrons away.

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

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.



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ARTICLE

Received 24 Jan 2013 | Accepted 27 Aug 2013 | Published 8 Oct 2013 DOI: 10.1038/ncomms3506

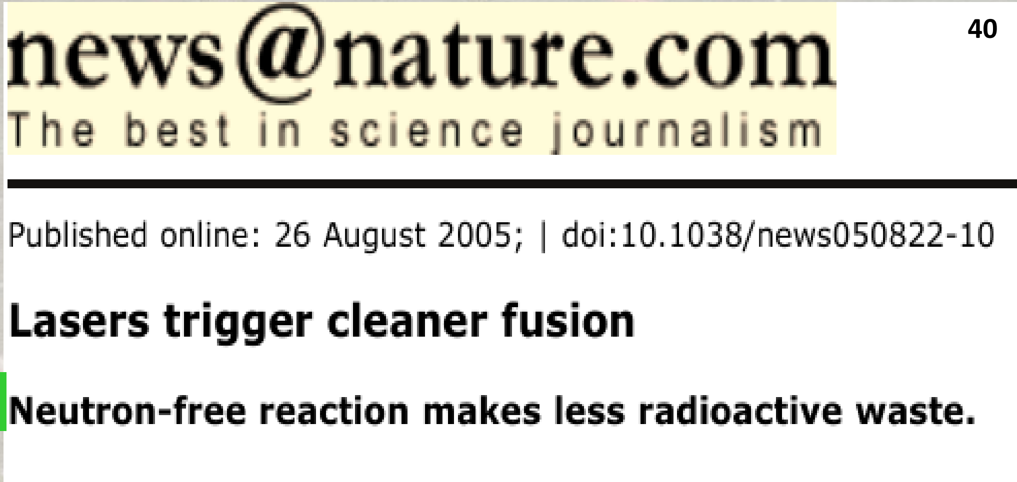
Fusion reactions initiated by laser-accelerated particle beams in a laser-produced plasma

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

Laser Contrast Ratio: $R = \frac{Pulse\ Intensity}{Prepulse/pedestal\ Intenity}$

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

Laser driven aneutronic proton-boron fusion



news@nature.com
The best in science journalism

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

Lasers trigger cleaner fusion

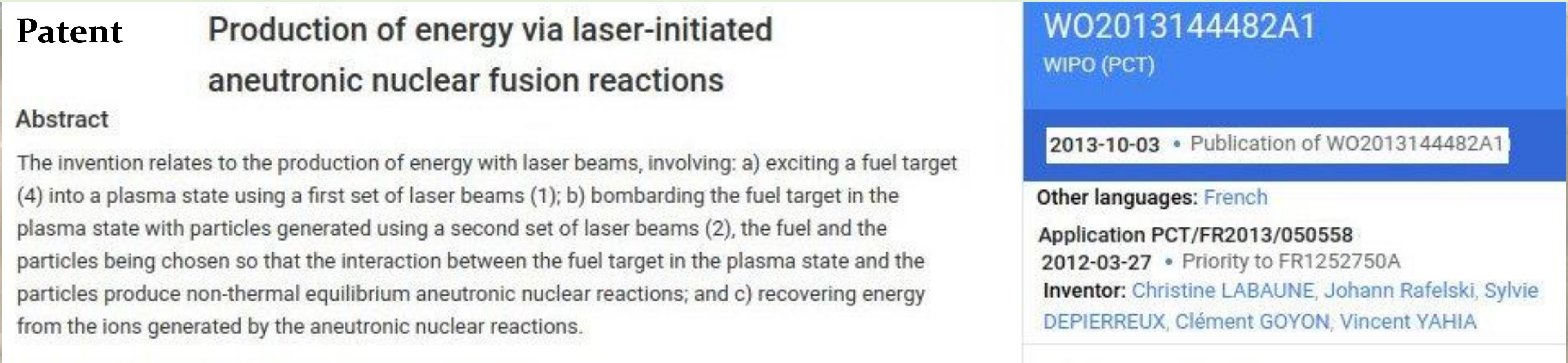
Neutron-free reaction makes less radioactive waste.

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

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

Appendix E: Comparison of dt-fusion power to fusion weapon reactions (all public information)

$$^{2}_{1}d + {}^{3}_{1}t \rightarrow {}^{4}_{2}He(3.56\text{ MeV}) + n(14.03\text{ MeV})$$

Giga-scale fusion patterned after the bomb

$$^{3}_{1}t + {}^{3}_{1}t \rightarrow {}^{4}_{2}He + n + n(11.33\text{ MeV})$$

Minor side-reactions with tritium and deuterium

LiD Sakharov thermonuclear fusion bomb reaction

$$^{6}_{3}Li + n \rightarrow {}^{4}_{2}He(2.05\text{ MeV}) + {}^{3}_{1}t(2.75\text{ MeV}) + 4.80\text{ MeV}$$

$$^{7}_{3}Li + n \rightarrow {}^{4}_{2}He + {}^{3}_{1}t + n - 2.466\text{ MeV}$$

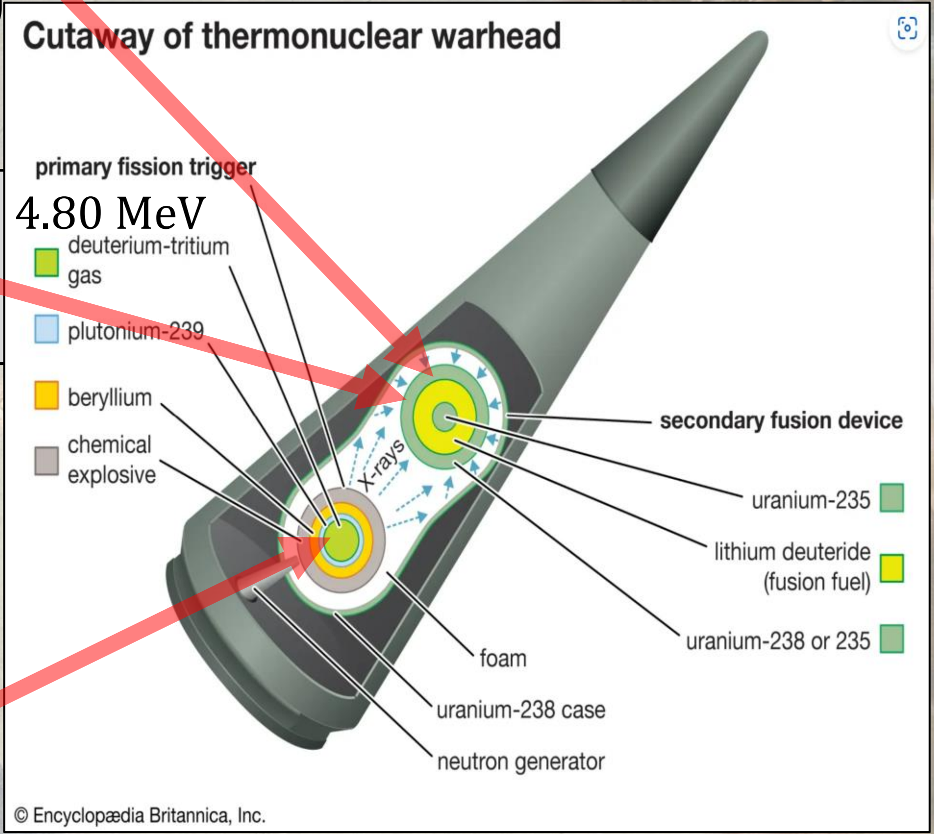
The mechanism to trigger a fusion bomb:

$$Po \rightarrow \alpha + X$$

$$\alpha + Be \rightarrow n + 3\alpha$$

Trigger Po fission

Trigger LiD/U fusion/fission



Cutaway of thermonuclear warhead

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