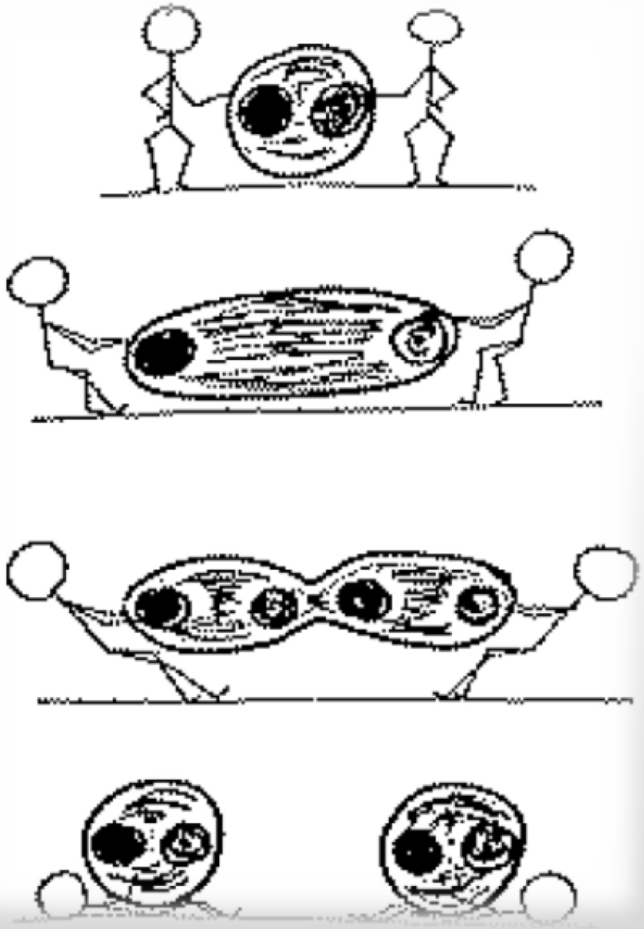
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

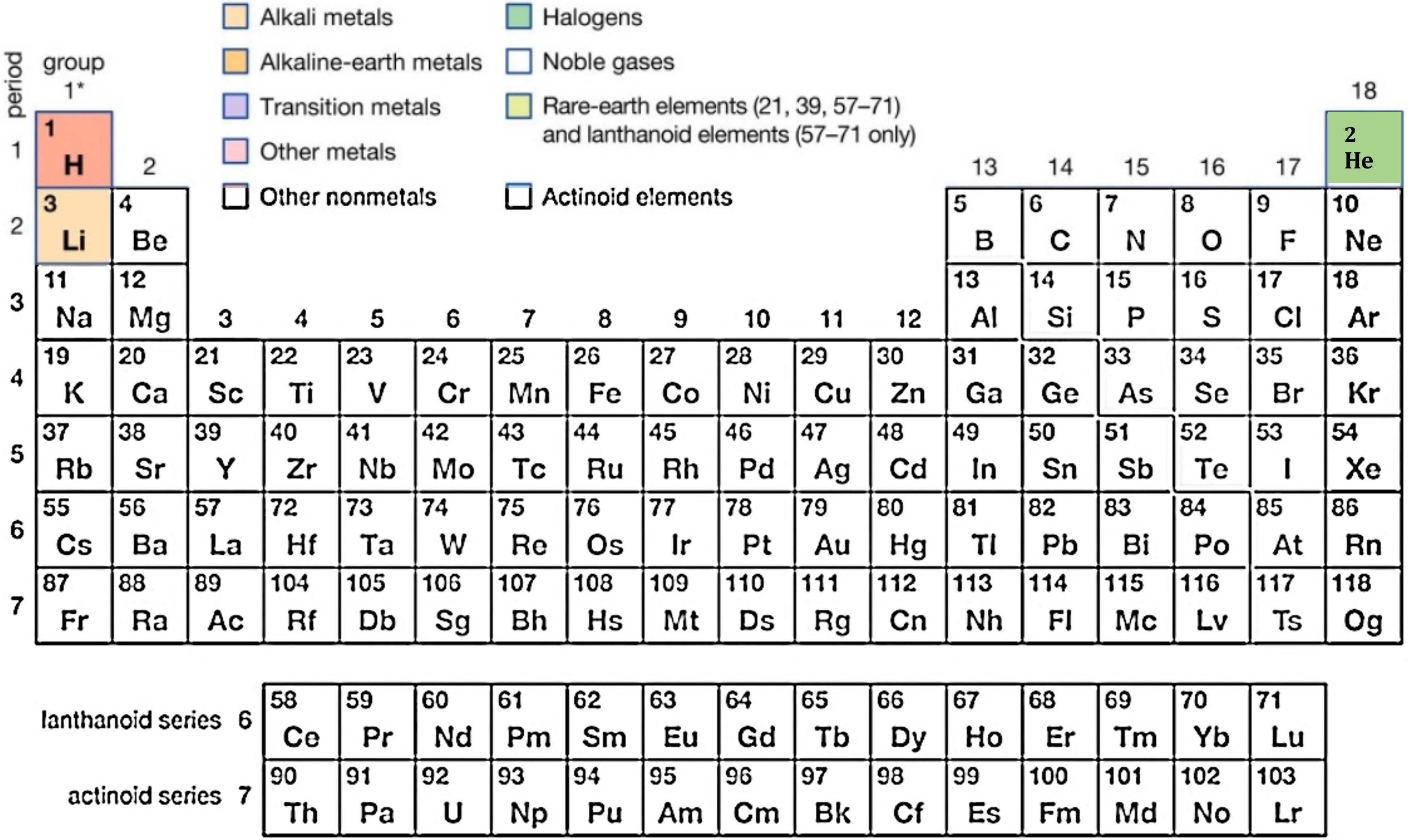
Nuclear astrophysics in plasma environment



Silvia Pisano*
Domenico Santonocito§

* *Centro Ricerche «Enrico Fermi» & Laboratori Nazionali di Frascati - INFN*
§ *Laboratori Nazionali del Sud- INFN*

Big-Bang Nucleosynthesis



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Big-Bang Nucleosynthesis

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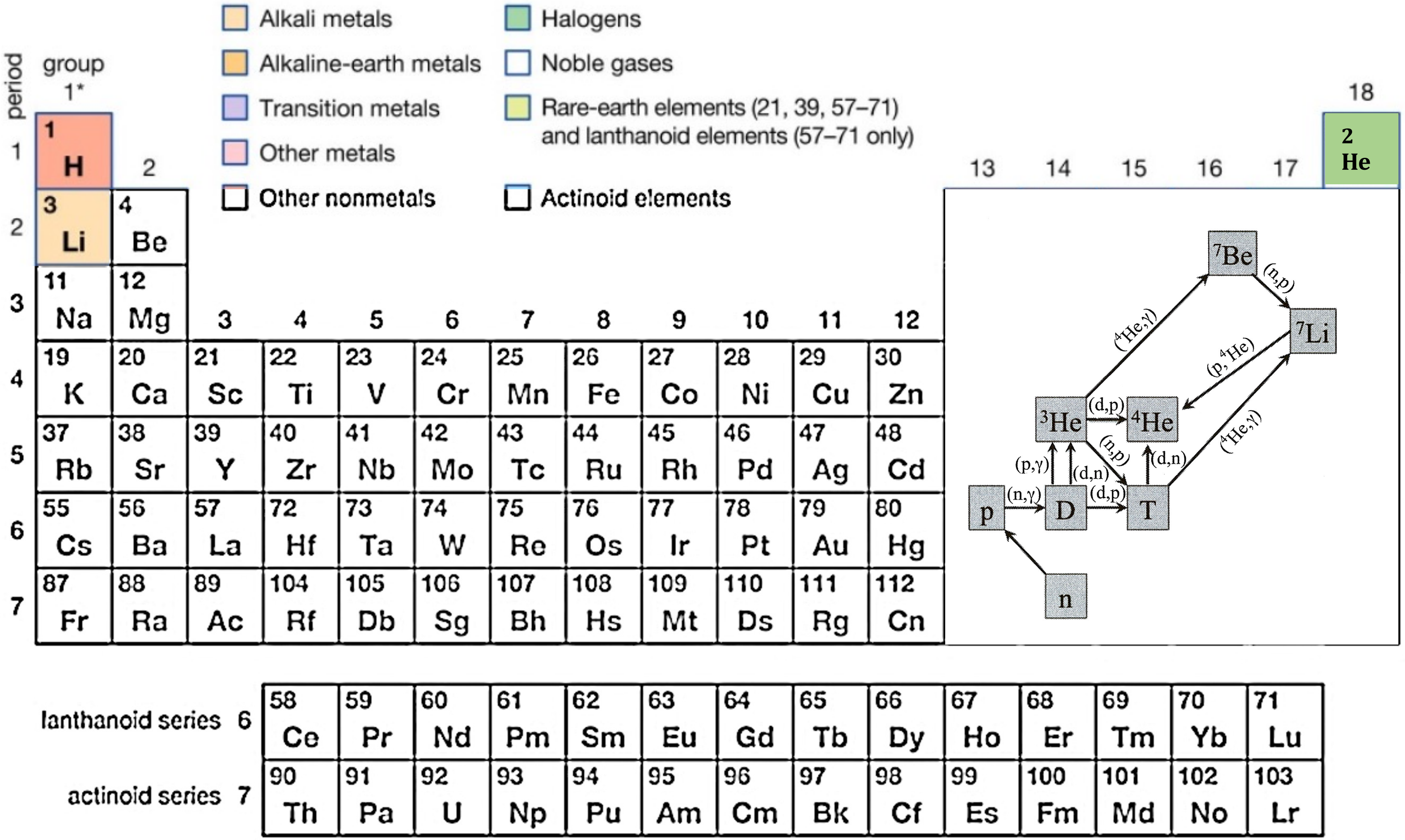
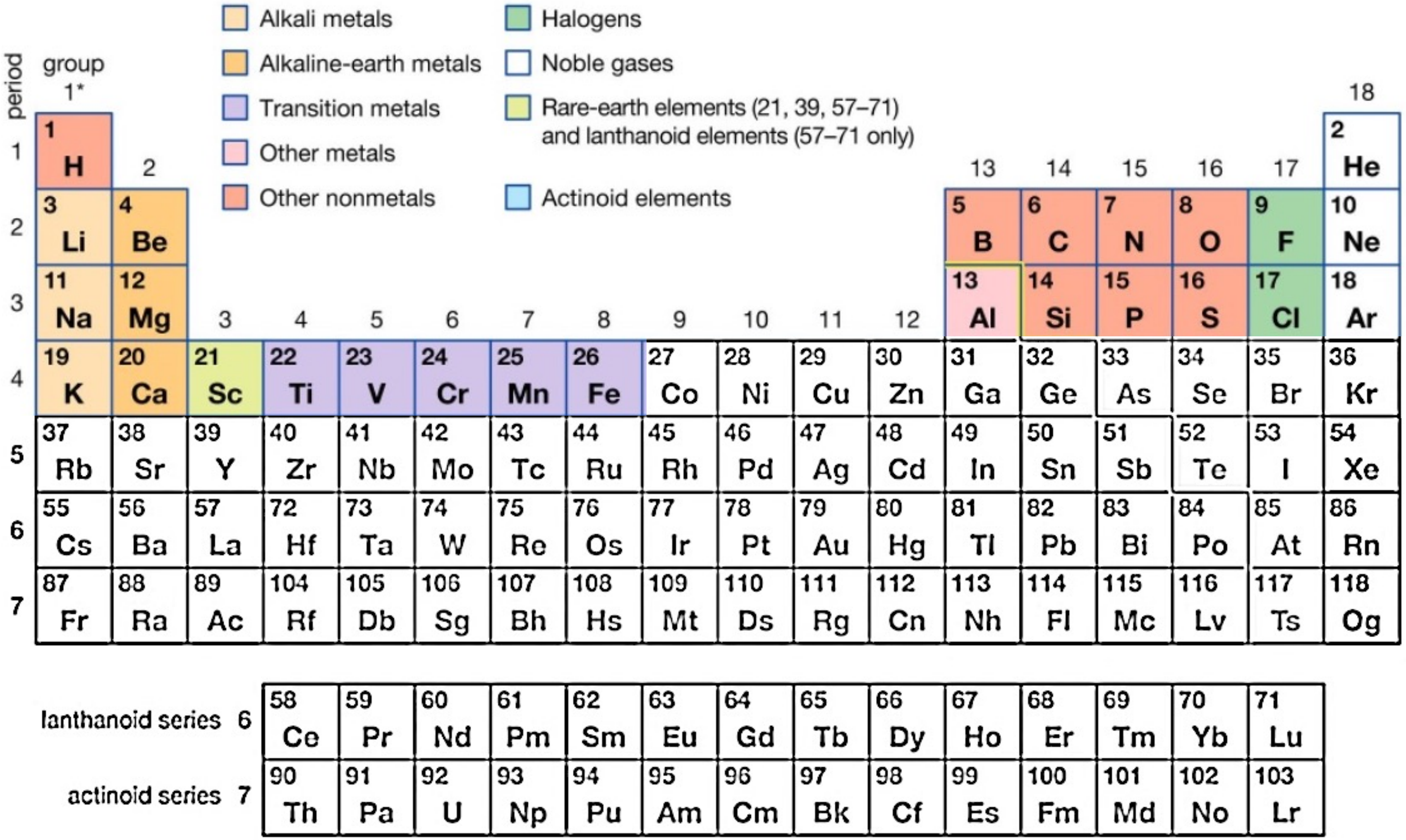


Stellar Nucleosynthesis



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Stellar Nucleosynthesis

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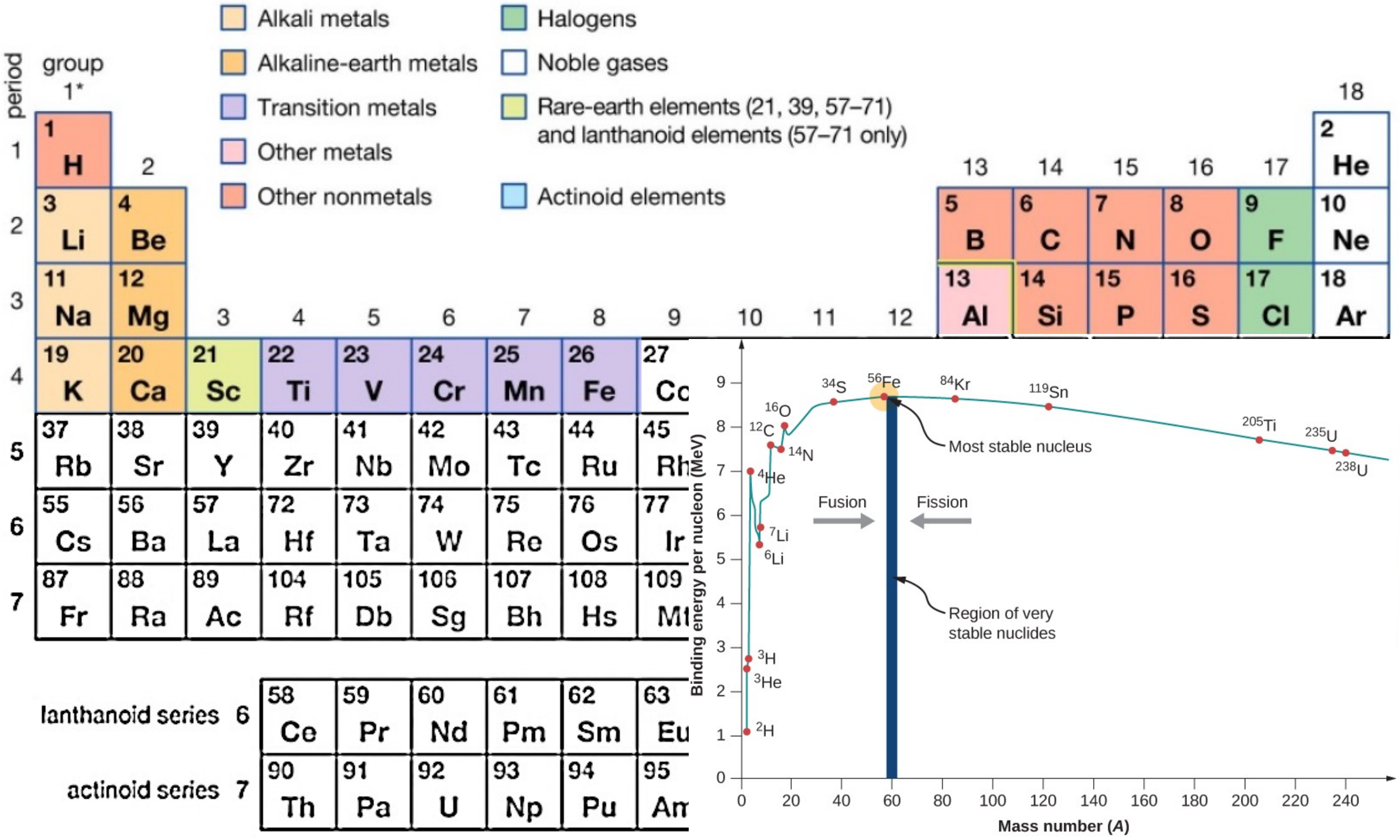
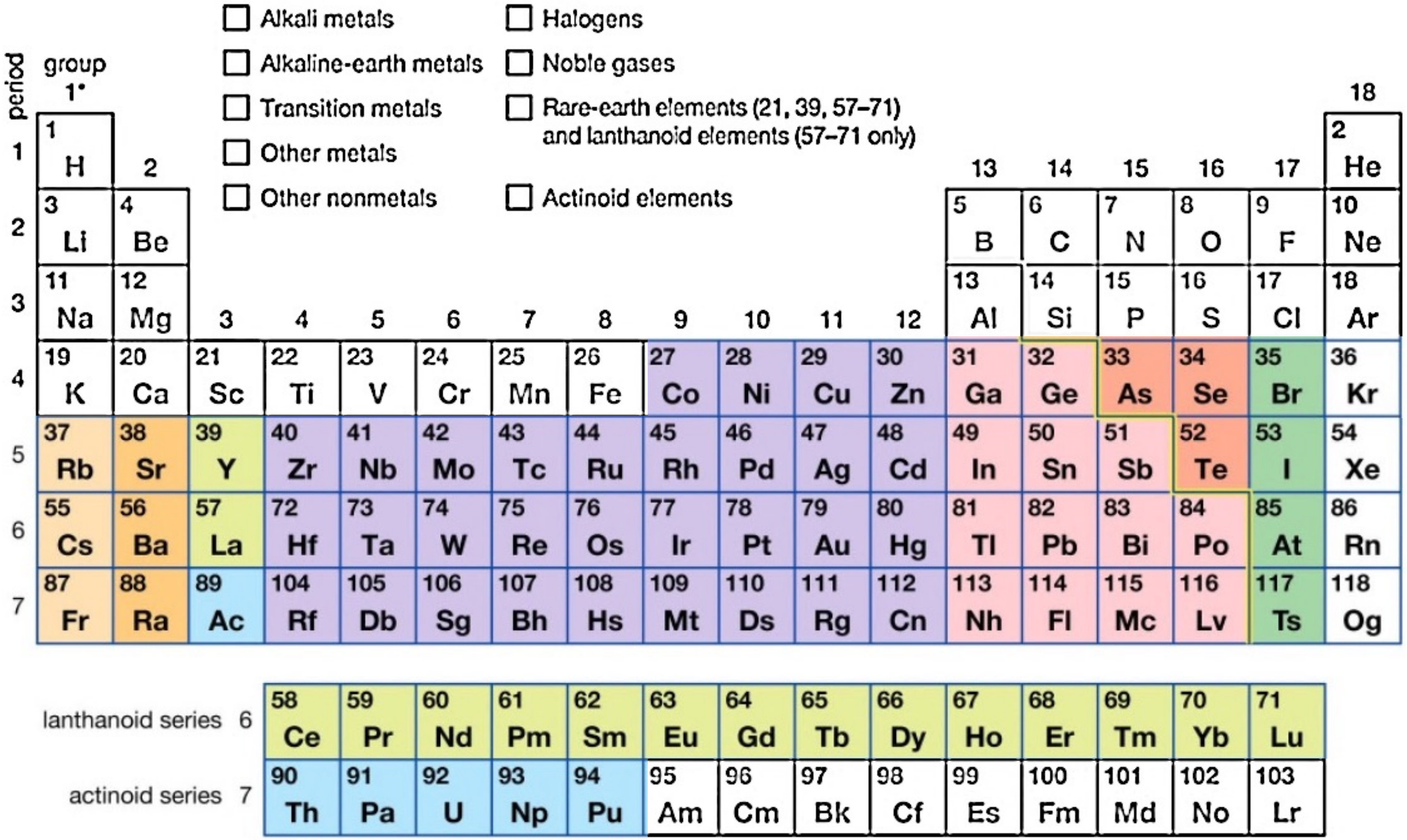


s- and *r*-process Nucleosynthesis



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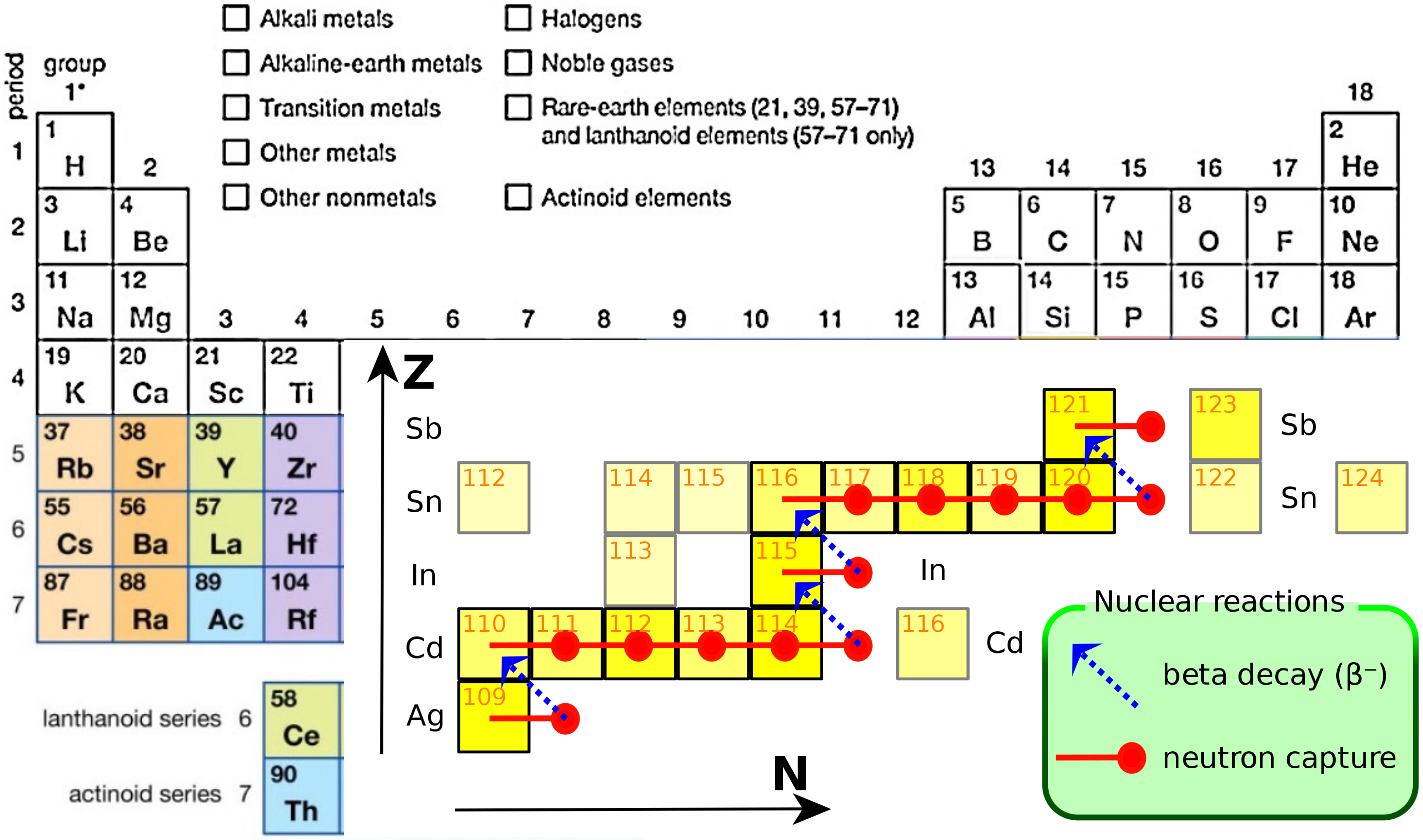

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β-decay investigation in matter

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In 1947 Segrè and Daudel pointed out that the **possibility to alter the decay rate of ^{7}Be by changing the electron density**, at least for low Z nuclei, an effect due to different chemical environment

PHYSICAL REVIEW VOLUME 71, NUMBER 4 FEBRUARY 15, 1947

Proceedings of the American Physical Society

MINUTES OF THE MEETING AT LOS ANGELES, CALIFORNIA, JANUARY 3–4, 1947

THE 276th meeting of the American Physical Society was held on Friday and Saturday, January third and fourth, 1947, at Los Angeles in Harris Hall of the University of Southern California. This was our first meeting at that University, which furnished excellent accommodations and management for our sessions. Our thanks are due particularly to R. E. Vollrath and G. L. Weissler. The attendance at the most populous session amounted to some 200. The four invited papers were admirable in content and presentation. The vice president of the Society was prevented by the grounding of his plane from presiding at the session of invited papers, and was replaced as Chairman by C. S. Van Atta. The other Chairmen were R. E. Vollrath and J. Kaplan.

J. KAPLAN
Local Secretary for the Pacific Coast
University of California
Los Angeles, California

A3. Possibility of Altering the Decay Rate of a Radioactive Substance. EMILIO SEGRÈ, *University of California, Berkeley.*—The radioactive decay constant of a substance decaying by orbital electron capture is proportional to $|\psi(0)|^2$ of the electrons. In the case of a light element like Be^7 it may be possible to alter this quantity by an appreciable amount by putting the Be in different chemical compounds. We would then have a slight change of the radioactive half-life of the Be in different compounds. The magnitude of the effect may be in the neighborhood of one percent, but it is practically impossible to give a quantitative estimate because the total change of $\psi(0)$ is affected by certain factors such as the density of the crystal, nature of the chemical bond, etc. They are both positive and negative, and have comparable magnitudes. To obtain a reliable estimate of the effect we require a more detailed knowledge of the wave functions for various compounds than is at present available. Experiments are in progress to detect the effect by comparing the half-life of Be^7 in Be metal with that in BeO or BeF_2.

Why plasma

Why plasma

Nucleosynthesis proceeds by nuclear fusion in massive stars until iron, where it stops because the fusion of still heavier nuclei needs energy instead of providing it.

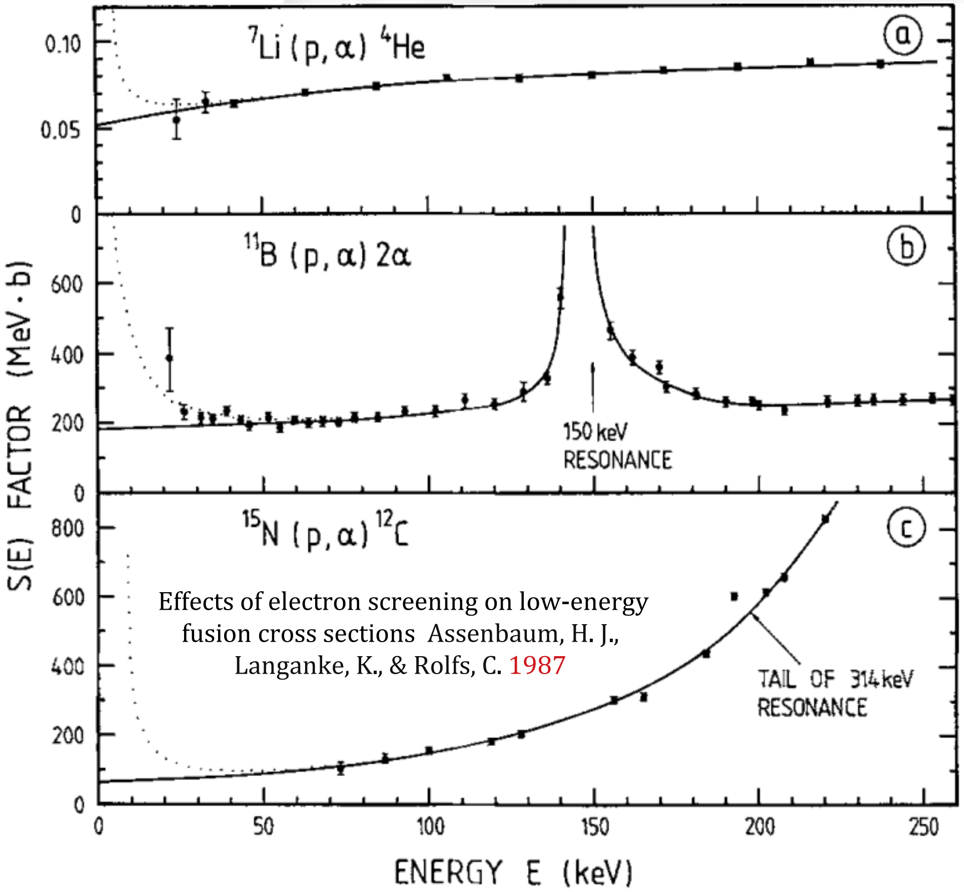
Heavier nuclei are created by an interplay between neutron capture and beta-decay.

A major difference exists between terrestrial and stellar conditions: stellar nucleosynthesis proceeds in a hot and dense environment which affects the degree of ionization of the atoms involved in the stellar nucleosynthesis.

This raises the question "whether or not" the high degree of ionization could induce any significant differences of the beta-decay properties with respect to neutral atoms.

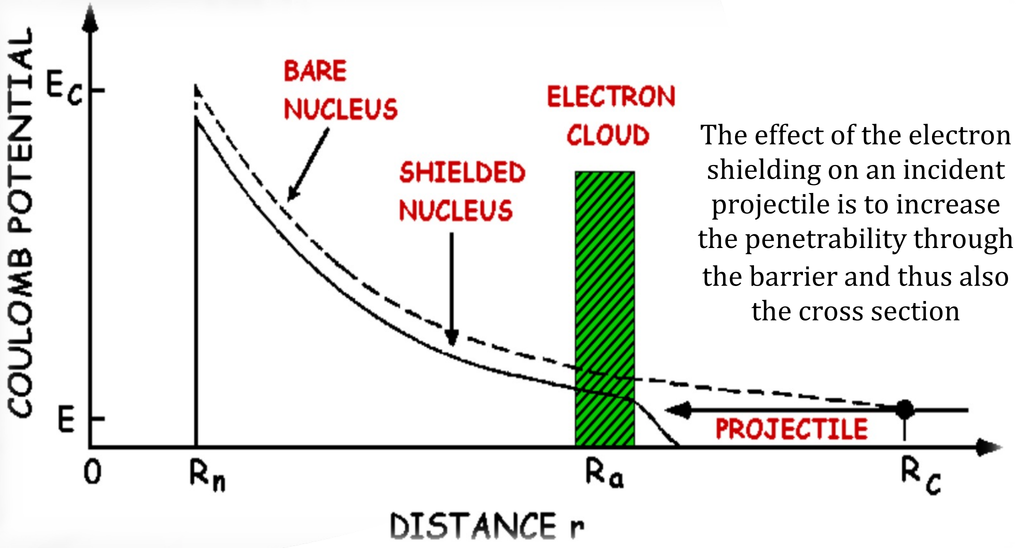
Why plasma: fusion processes

ELECTRON SCREENING AND THERMONUCLEAR REACTIONS E. E. SALPETER 1954



Effects of electron screening on low-energy fusion cross sections Assenbaum, H. J., Langanke, K., & Rolfs, C. 1987

Relatively small enhancements due to electron screening could cause significant errors in the extrapolation to lower energies, if the cross-section curve is forced to follow the trend of the enhanced cross sections without correcting for screening.



The effect of the electron shielding on an incident projectile is to increase the penetrability through the barrier and thus also the cross section

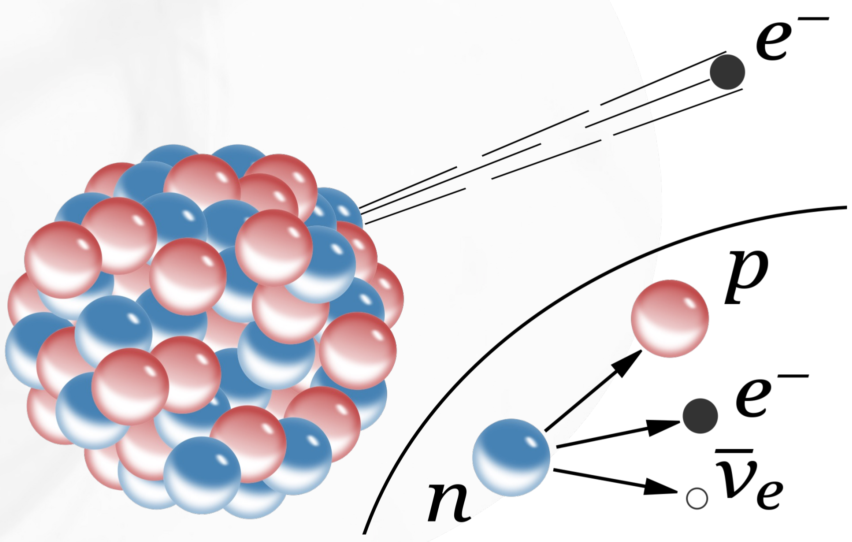
Why plasma: β-decays

Stellar nucleosynthesis proceeds in a hot and dense environment which affects the degree of ionization of the atoms involved in the stellar nucleosynthesis.

What happens when atoms are highly ionized?

The beta decay in highly ionized atoms shows important variations compared to neutral species

1. Electron Capture becomes impossible in fully ionized atoms.
2. Bound state β-decay typically marginal can become important.



https://www.frontiersin.org/research-topics/25146/nuclear-physics-and-astrophysics-in-plasma-traps

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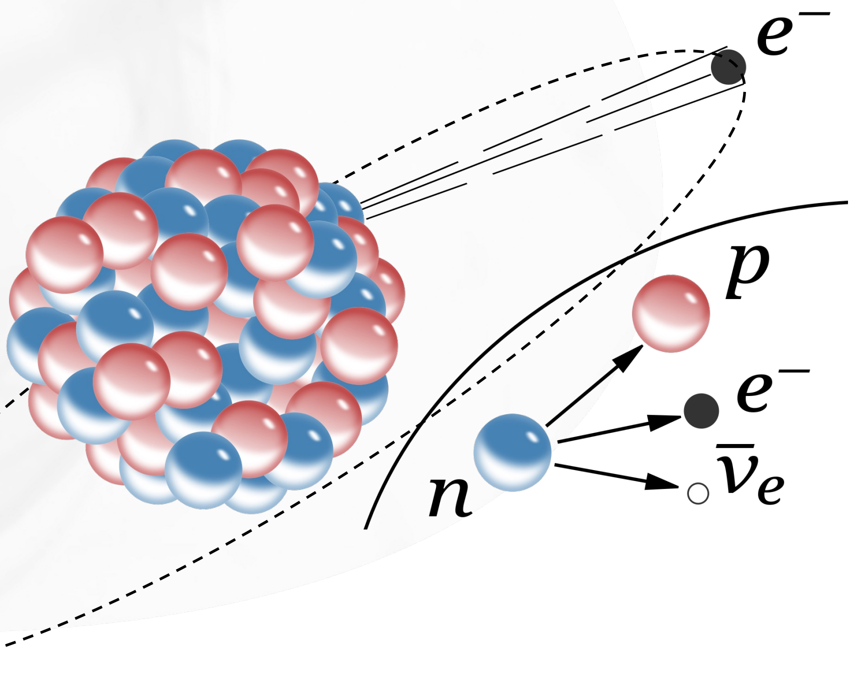
Bound-state β-decay is a nuclear β- decay process in which an electron is created in a previously unoccupied atomic orbital rather than in the continuum.



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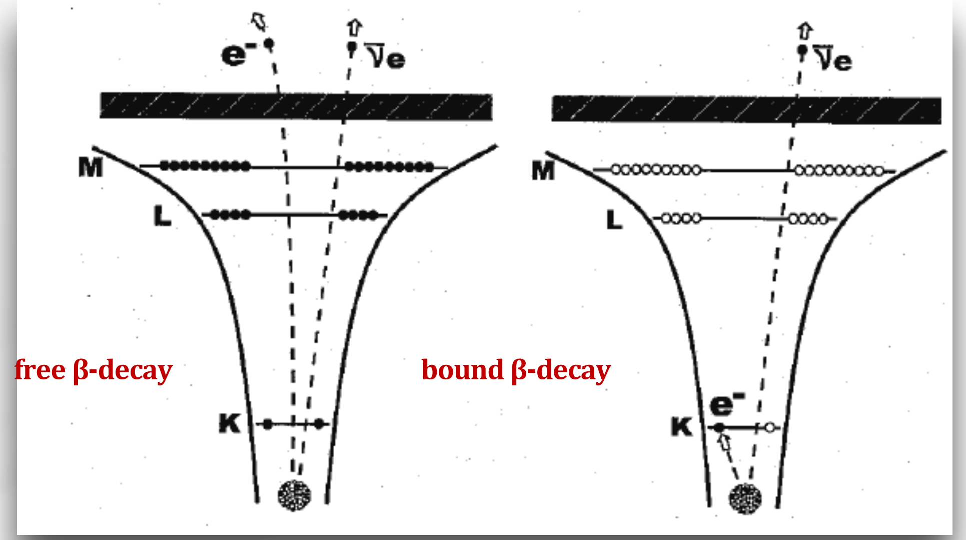

Y. Litvinov and F. Bosh: Rep. Prog. Phys. 74, 016301 (2011)

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Bound-state β-decay is a nuclear β- decay process in which an electron is created in a previously unoccupied atomic orbital rather than in the continuum.

Example: Bare $^{187}Re^{75+}$ ions decay, due to the bound-state beta decay, **becomes 9 orders of magnitude faster than neutral ^{187}Re atoms with a half-life of 42 Gyr.**

Q-value modifications: *in a stellar plasma, ions are embedded in a cloud of charges, both positive and negative. These charges create EM fields which act as perturbation to the atomic/ionic levels leading to corrections of Q-values which affects the decay rates.*

F. Bosch at al., Observation of Bound-State β^- Decay of Fully Ionized ^{187}Re: ^{187}Re–^{187}Os Cosmochronometry, Phys. Rev. Lett. 77, 1996

Why plasma: β-decays

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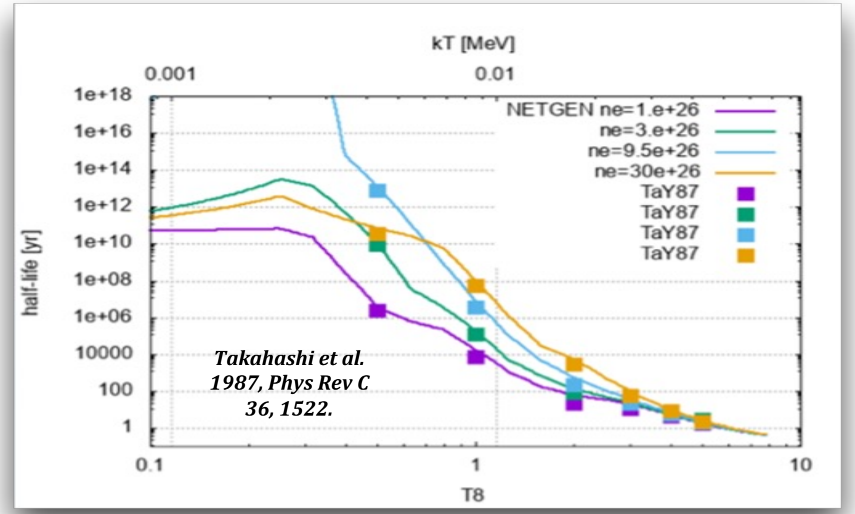
Stellar plasma environment (ρ, T) can play a major role in modifying the rates at the branching point in s-process nucleosynthesis. *Temperature dependent variations evaluated in the seminal work of Takahashi and Yoko*i.



https://journals.aps.org/prc/abstract/10.1103/PhysRevC.36.1522

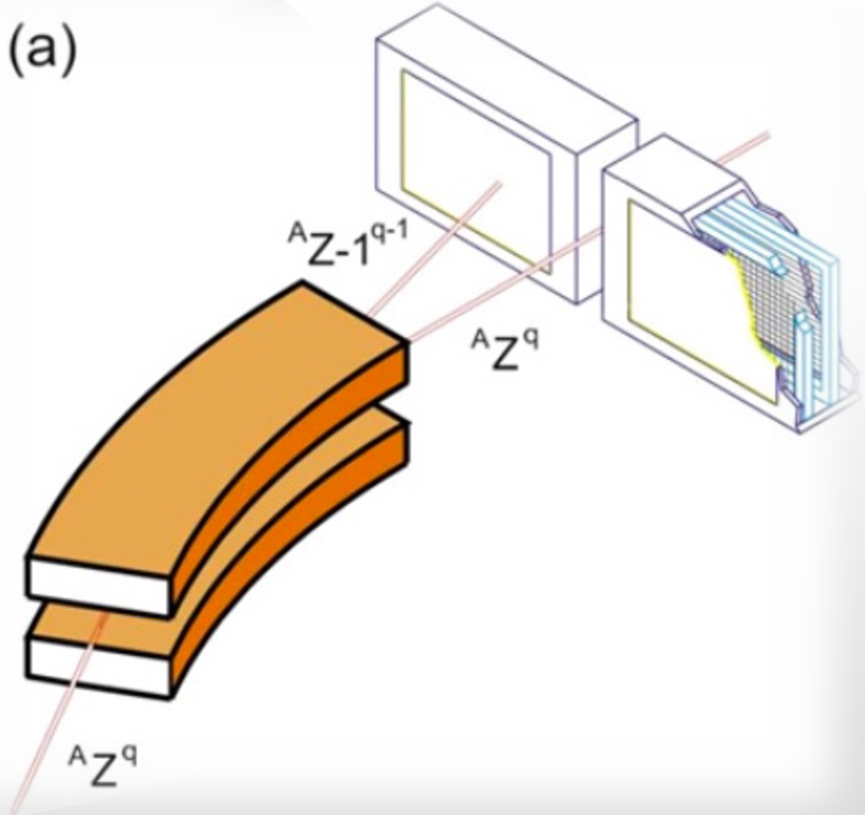
Storage ring experiments

1. β-unstable nuclei produced at high atomic charge state (projectile fragmentation or fission)

2. Separation of reaction products (fragment separator)

3. Depending on nuclear charge and the **m/q acceptance** of the ring up to three charge state can be stored in the ring

4. For cases in which the decay induces a change in m/q larger than the acceptance the decay products can be measured by in-ring particle detectors (multiwire proportional chambers or Si detector telescopes)



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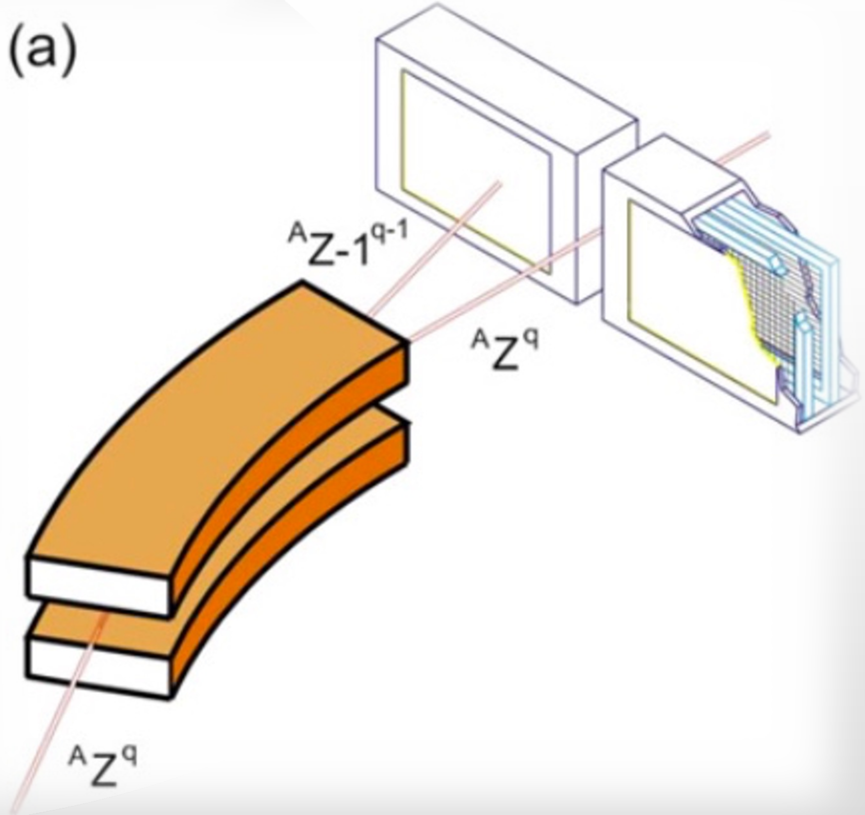


Storage ring experiments are incapable of exploring the rate modifications due to charge state distributions

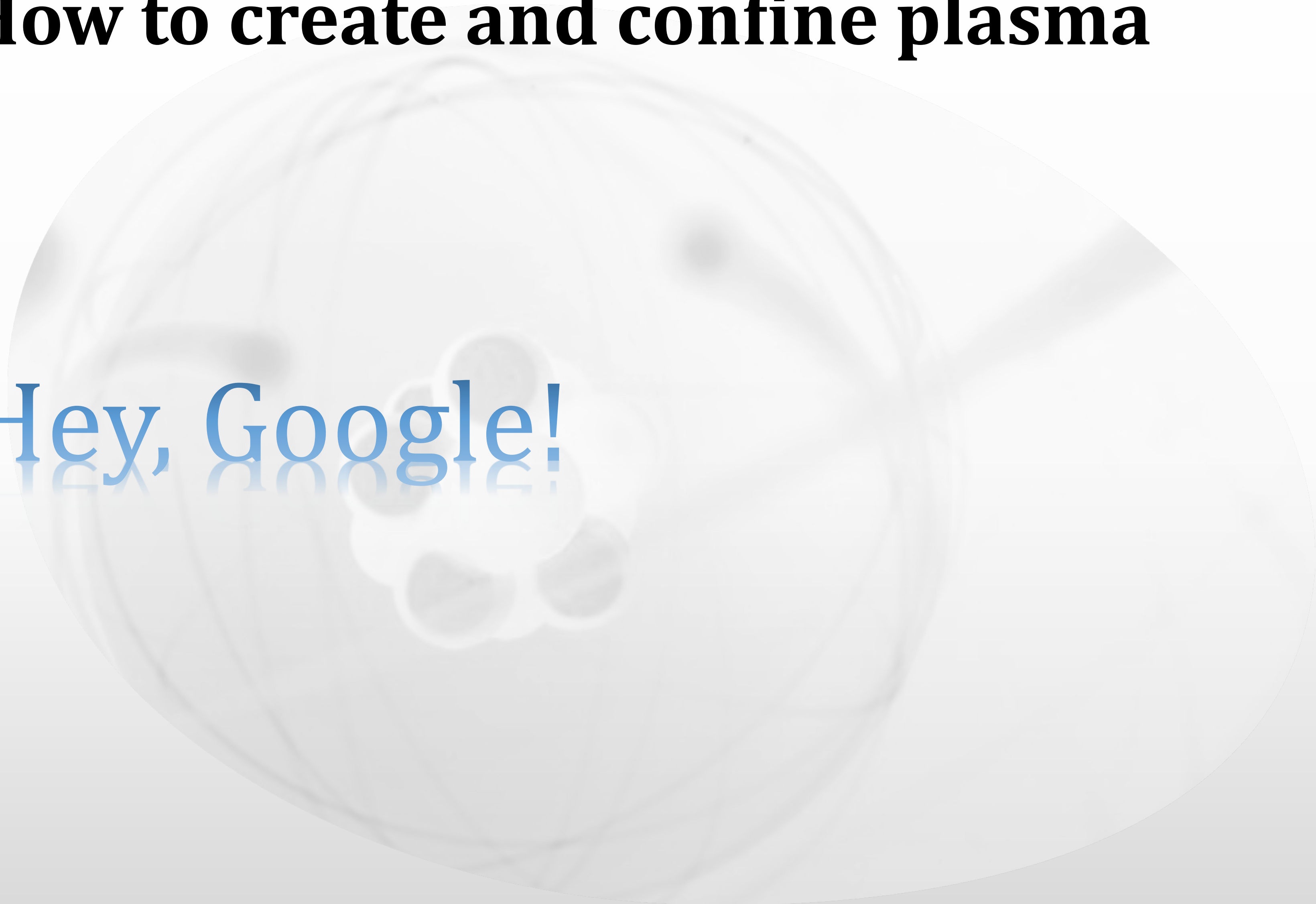
How to reproduce stellar like conditions in a laboratory?

How to reproduce stellar like conditions in a laboratory?

→ **We need to create and confine a plasma to be able to study the β-decay in such environment**

How to create and confine plasma

How to create and confine plasma



Hey, Google!

How to create and confine plasma

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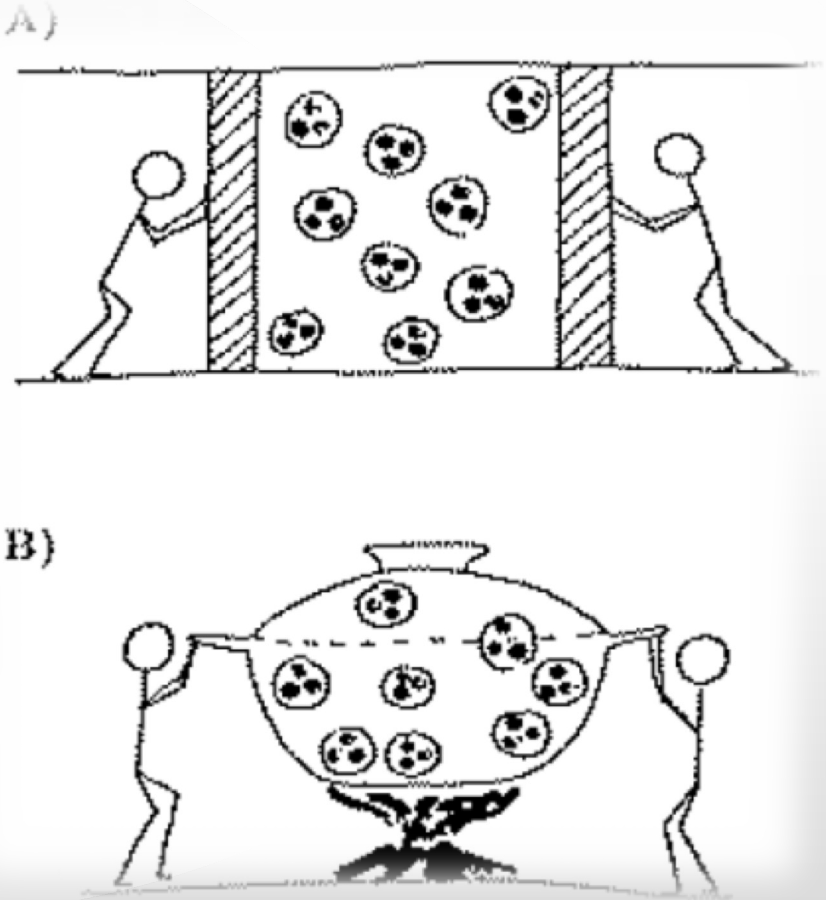
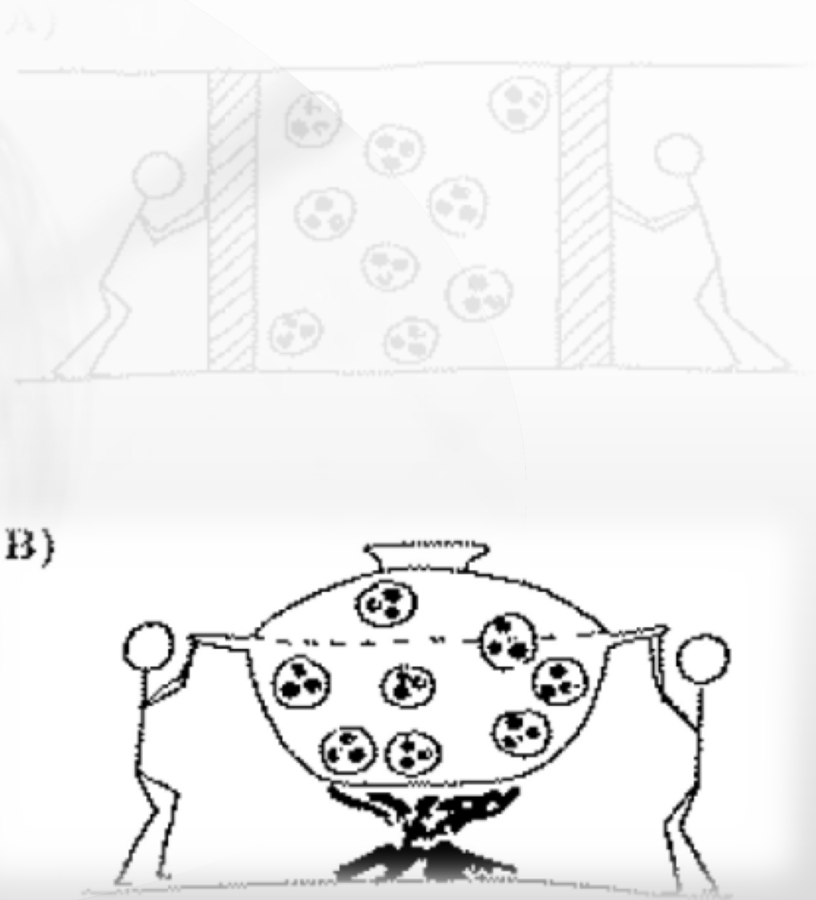


How to create and confine plasma



How to create plasma

It is composed of

1. Positively charged ions
2. Electrons
3. Neutrals

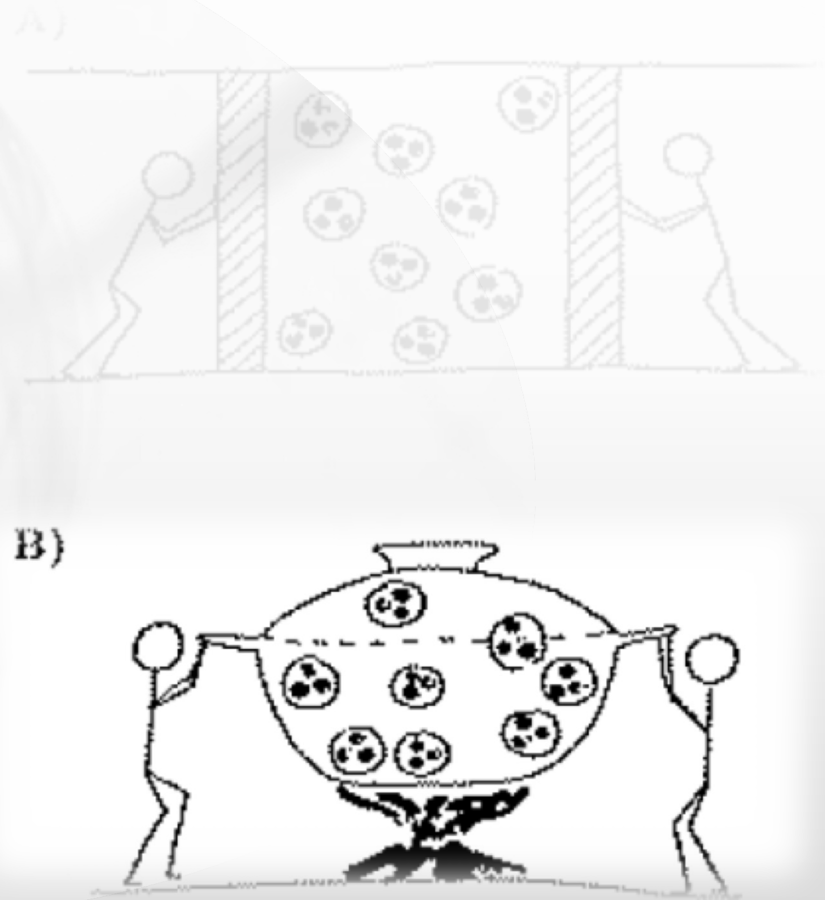
It is a quasi-neutral gas made of charged particles exhibiting a collective behaviour.
Saha law describing the ionization state of a gas:

$$\frac{n_i}{n_n} = 2.4 \times 10^{21} \frac{T^{3/2}}{n_e} e^{-\frac{U_i}{kT}}$$

U_i = ionization potential
n_e = electron density
n_i = ion density
n_n = neutral density

To be compared to the value on Earth:

$$\frac{n_i}{n_n} = 10^{-122}$$



How to create and confine plasma

It is composed of

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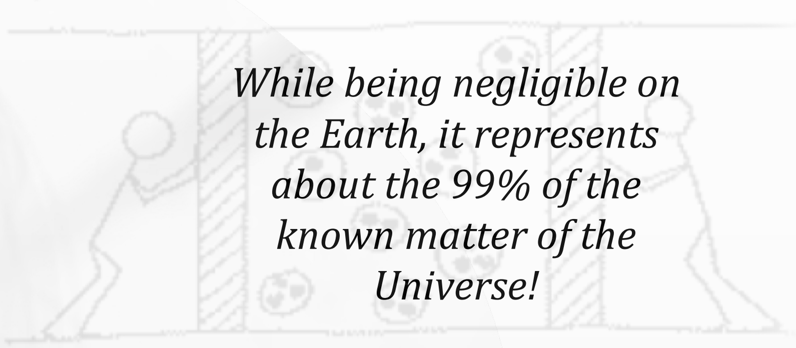
It is a quasi-neutral gas made of charged particles exhibiting a collective behaviour.

Its key properties are:

- **Quasi neutrality** → Strength and range of the electric force and the good conductivity of plasma ensures that densities of positive and negative charges in any sizeable region are ”equal”. It is directly connected to *Debye lenght*
- **Display collective behaviour** → particle motion in a defined region will depend on the general status of the system

A)



While being negligible on the Earth, it represents about the 99% of the known matter of the Universe!

B)

How to create and confine plasma

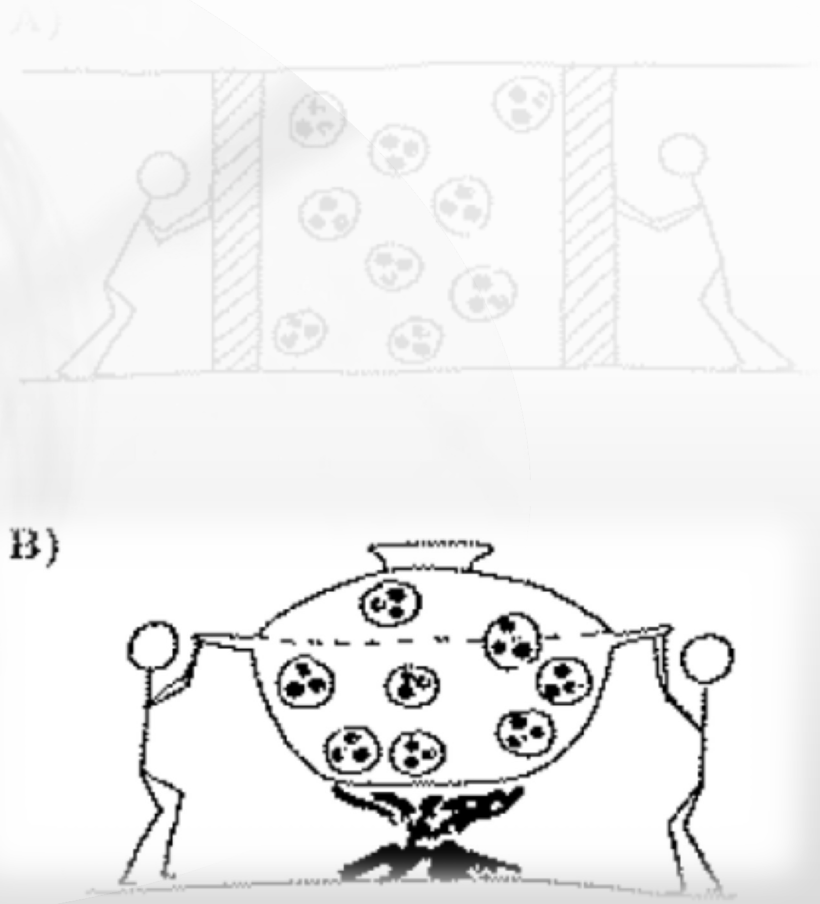
Weakly ionised plasma is a mixture of different gases: neutral gas, ion gas and electron gas.

Electrons and ions can have different distribution functions (close to a Maxwellian) and therefore different temperatures.

Under the action of EM field electron gain more energy than ions. Their mean energy will exceed the mean energy of the ions and neutrals → $T_e \gg T_i, T_n$

In plasma temperatures are measured in eV → $kT = 1eV$ corresponds to a $T = 11600K$

- $kT_e = 1 \div 10^4$ eV for electrons (*i.e.* $10^4 \div 10^8$K)
- $kT_i = 0.03 \div 1$ eV for ions (*i.e.* about 10^4K)



How to create and confine plasma

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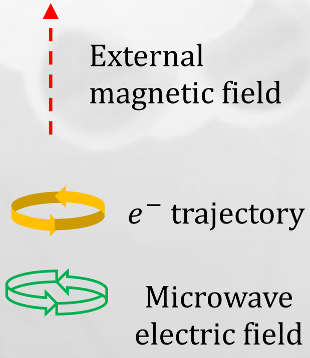
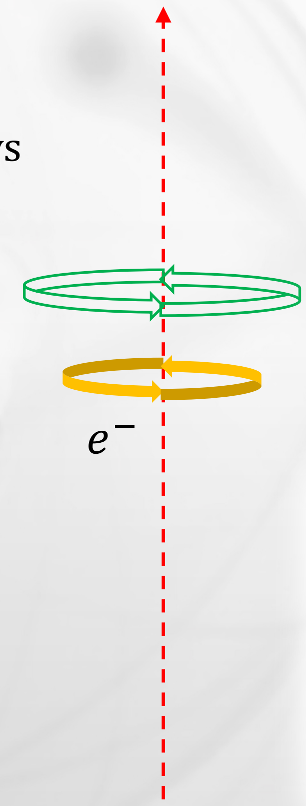
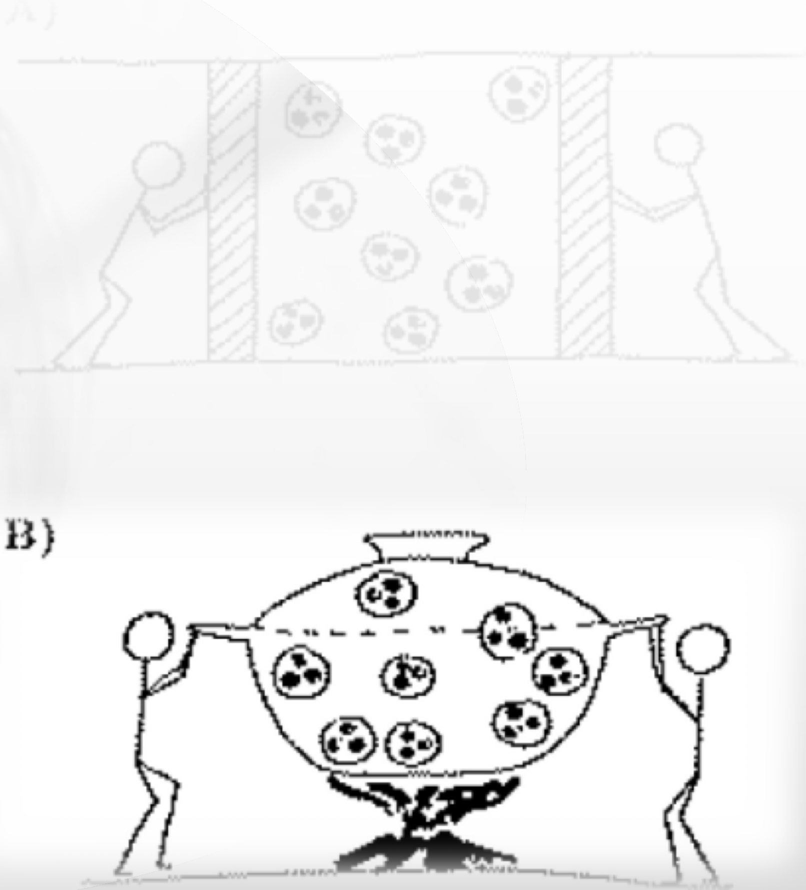
Electron Cyclotron Resonance method

Electromagnetic (*microwave*) propagation plays a fundamental role since the plasmas are typically generated and heated mainly through the interaction of the electrons with EM waves.

High charge state ions are primarily produced by **sequential impact ionization**: the ions must remain in the plasma long enough (tens of ms) to reach high charge states.







How to create and confine plasma

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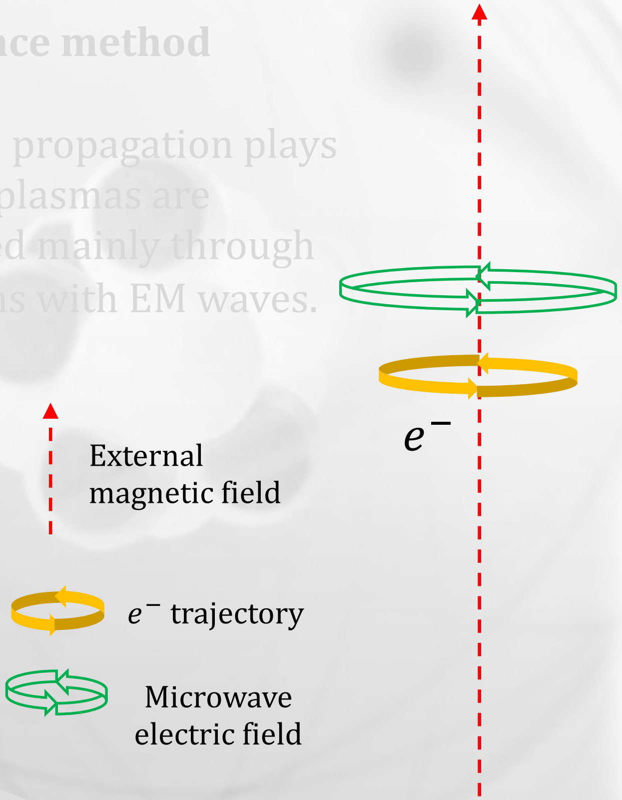

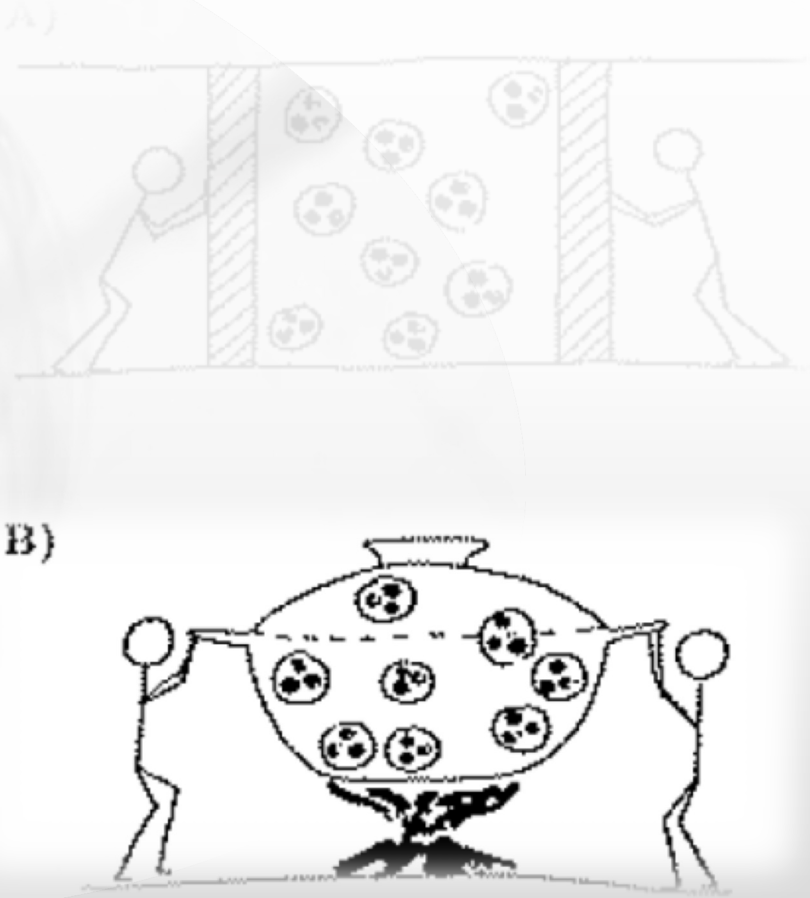

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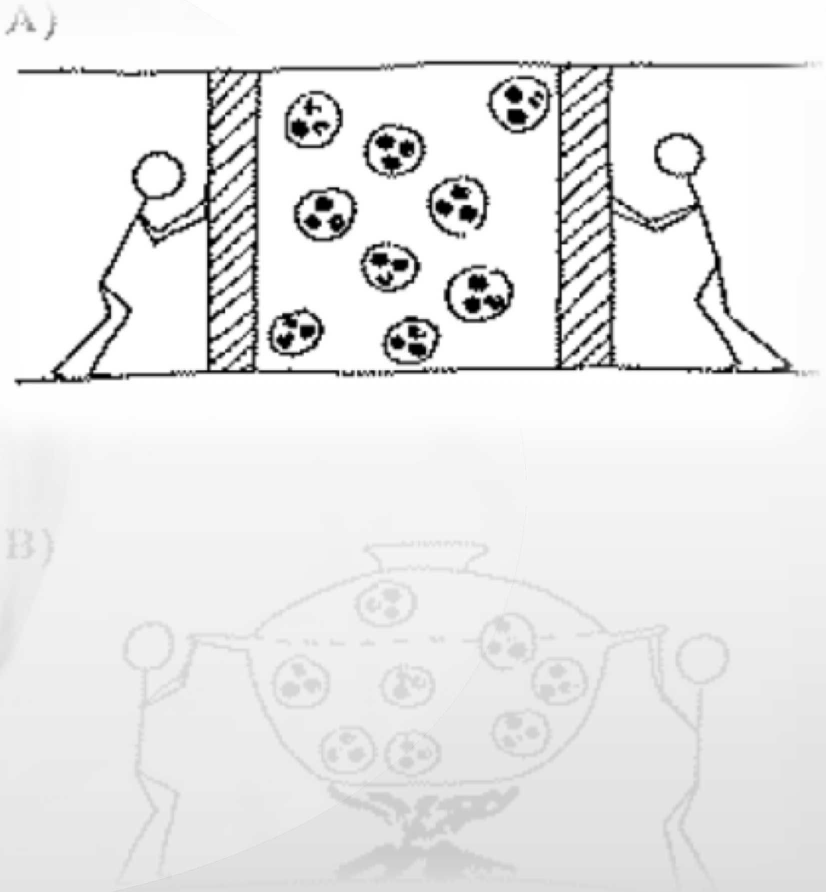

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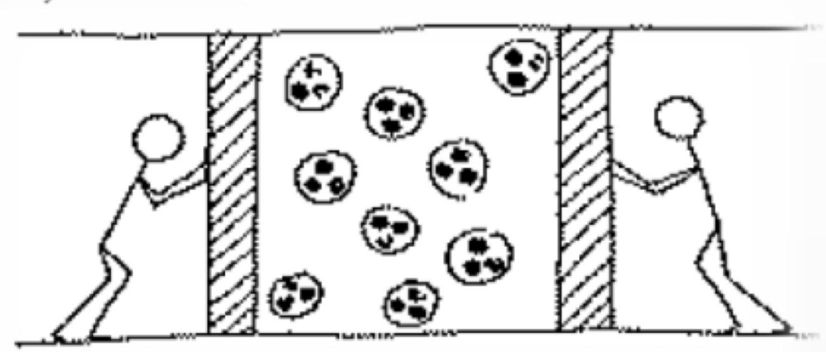
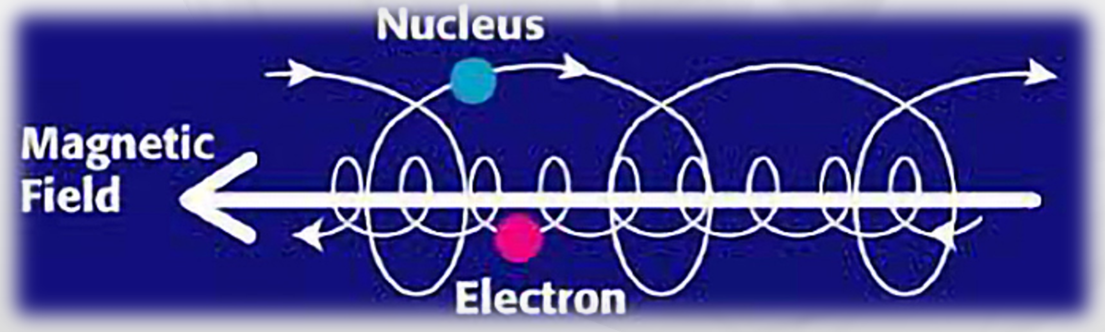


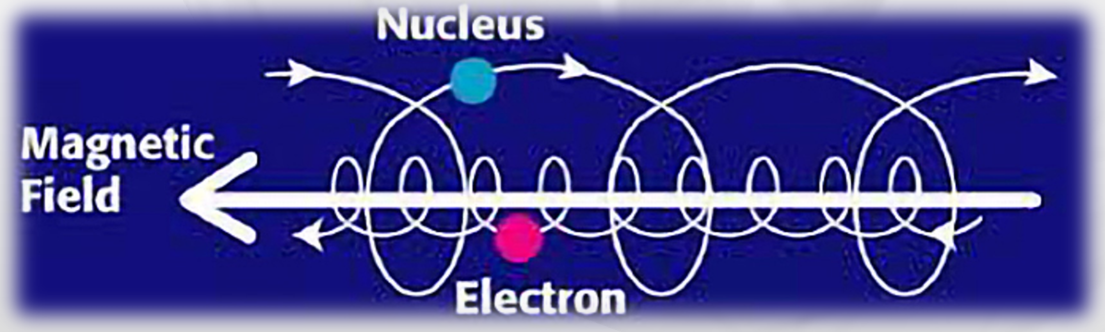
$\overrightarrow{F_L} = q\,\vec{v} \times \vec{B}$ → Magnetic fields force charged particles to reduce freedom degrees: electrons spiralyze around the field lines and can be trapped for several milliseconds in mirror machines or toroidal.



How to create and confine plasma

The Lorentz force $\overrightarrow{F_L}$ exerted by a static magnetic field $\vec{B}$ on particles of mass m having an elementary charge e causes a circular motion, with a (cyclotron) radius

$$r_B = \frac{mv}{eB}$$



It is associated to a cyclotron frequency ω_B independent on particle velocity and given by

$$\omega_B = \frac{eB}{m}$$

How to create and confine plasma

Mirror structures

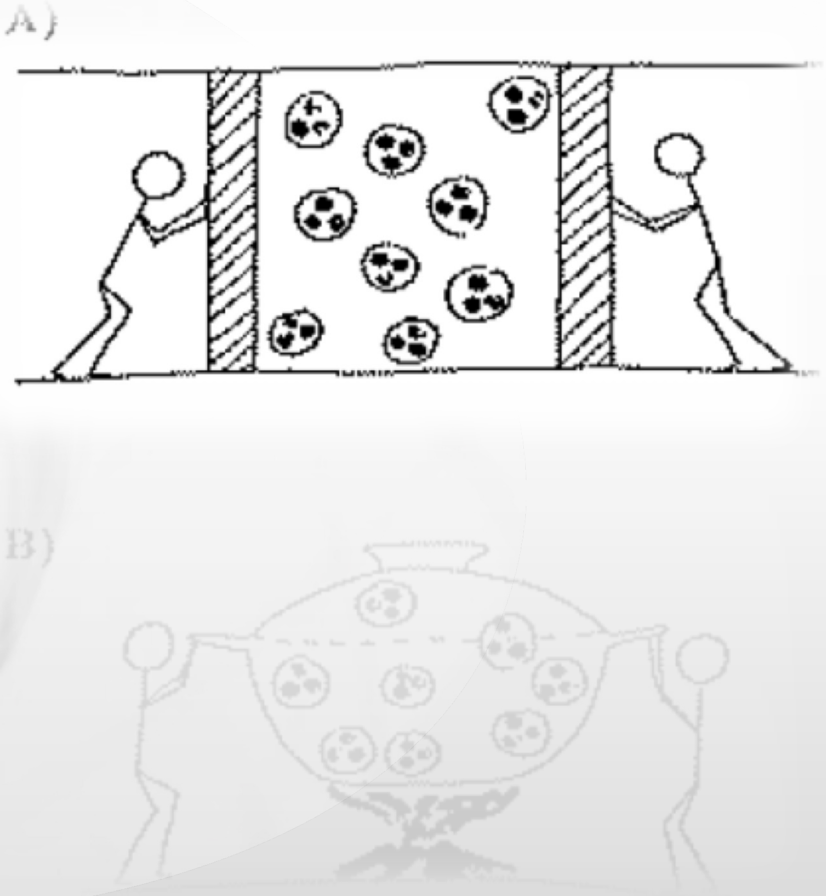
They have axial symmetry and can be produced using superconducting coils. To produce trapping:

1. *Magnetic field should display a gradient in a direction parallel to the field lines*

2. *In a simple mirror the field has a radial component*

3. *Magnetic moment:* $\mu \equiv \frac{1}{2}\frac{mv^2{}_{\perp}}{B}$

4. *Mirror effect*



How to create and confine plasma

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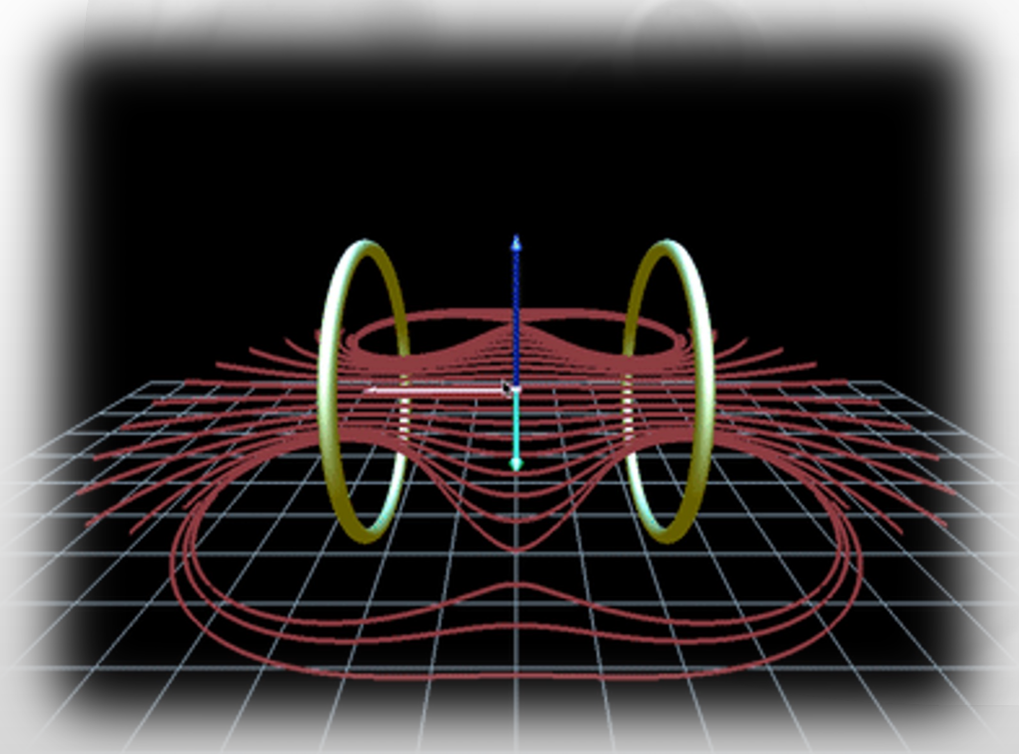
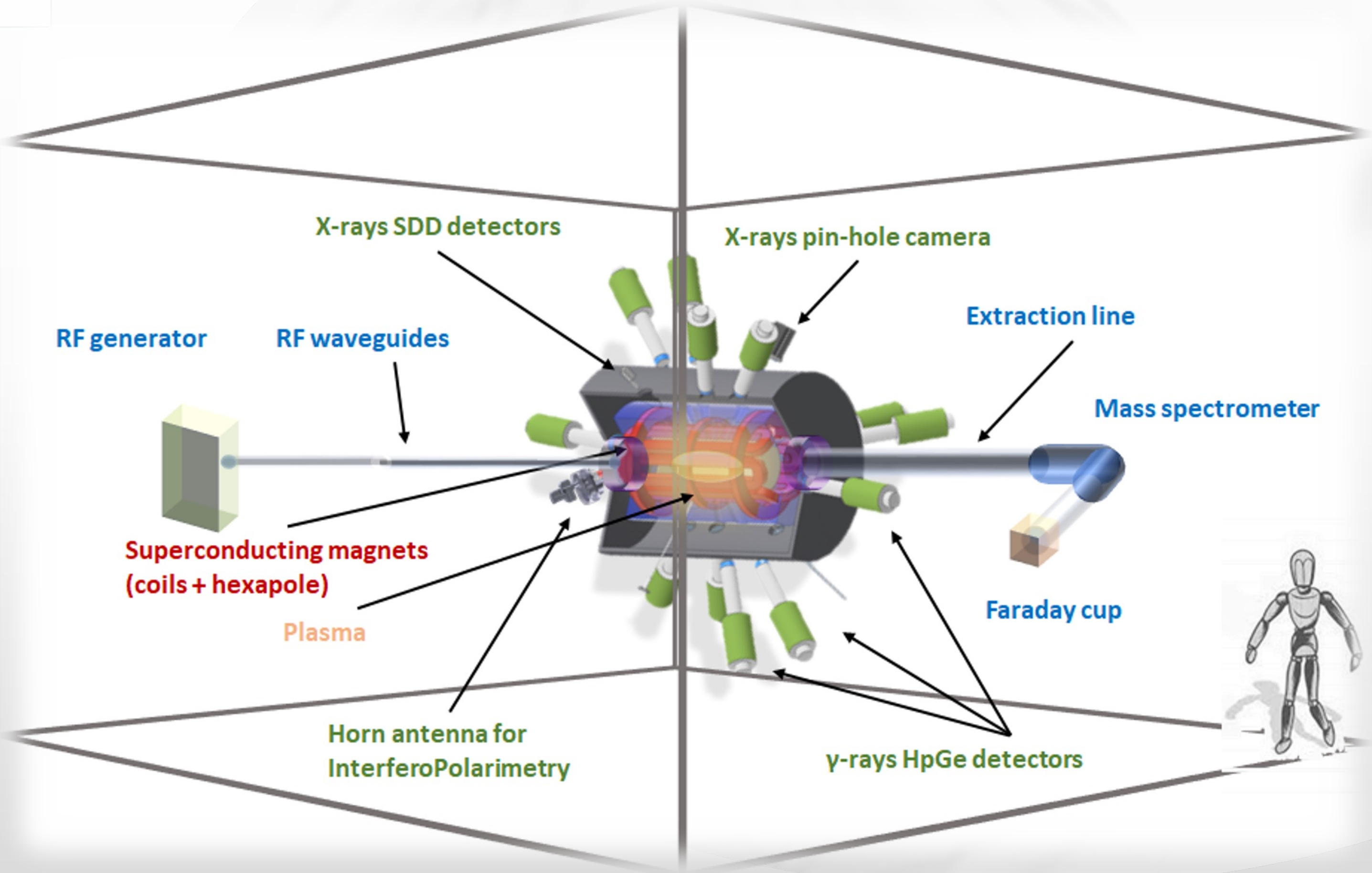


The PANDORA experiment



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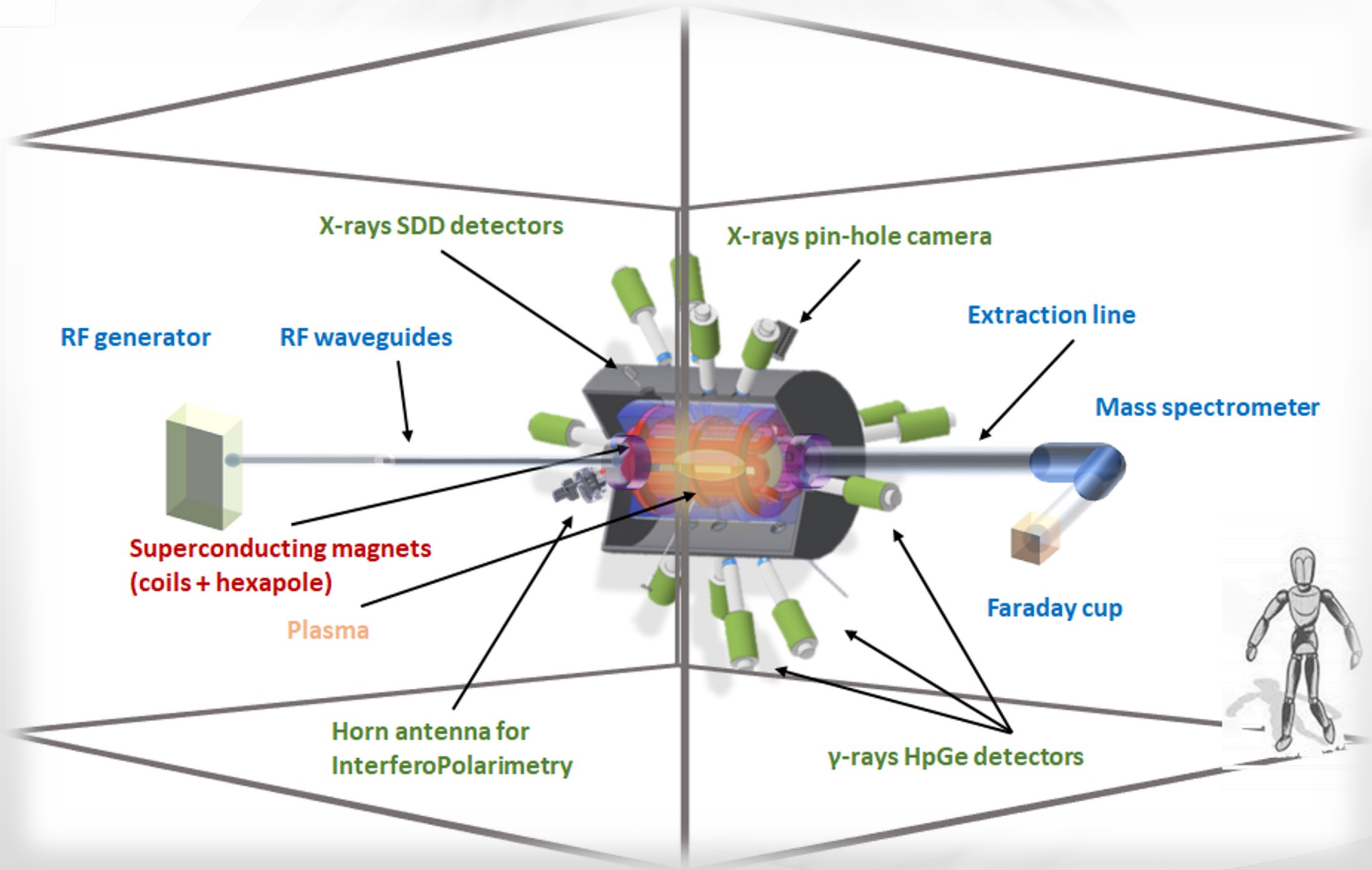
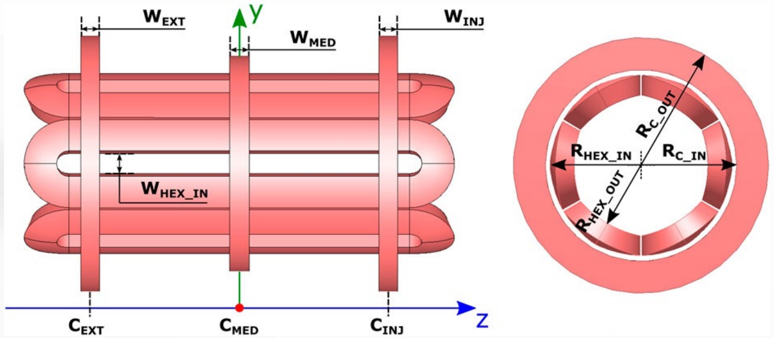
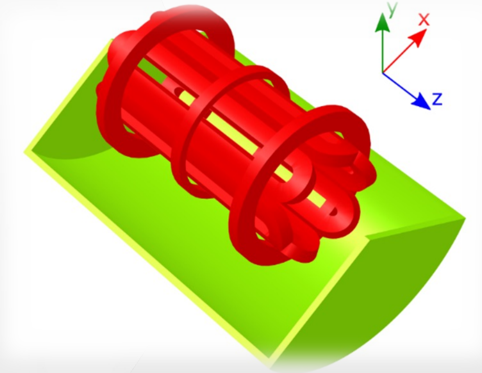


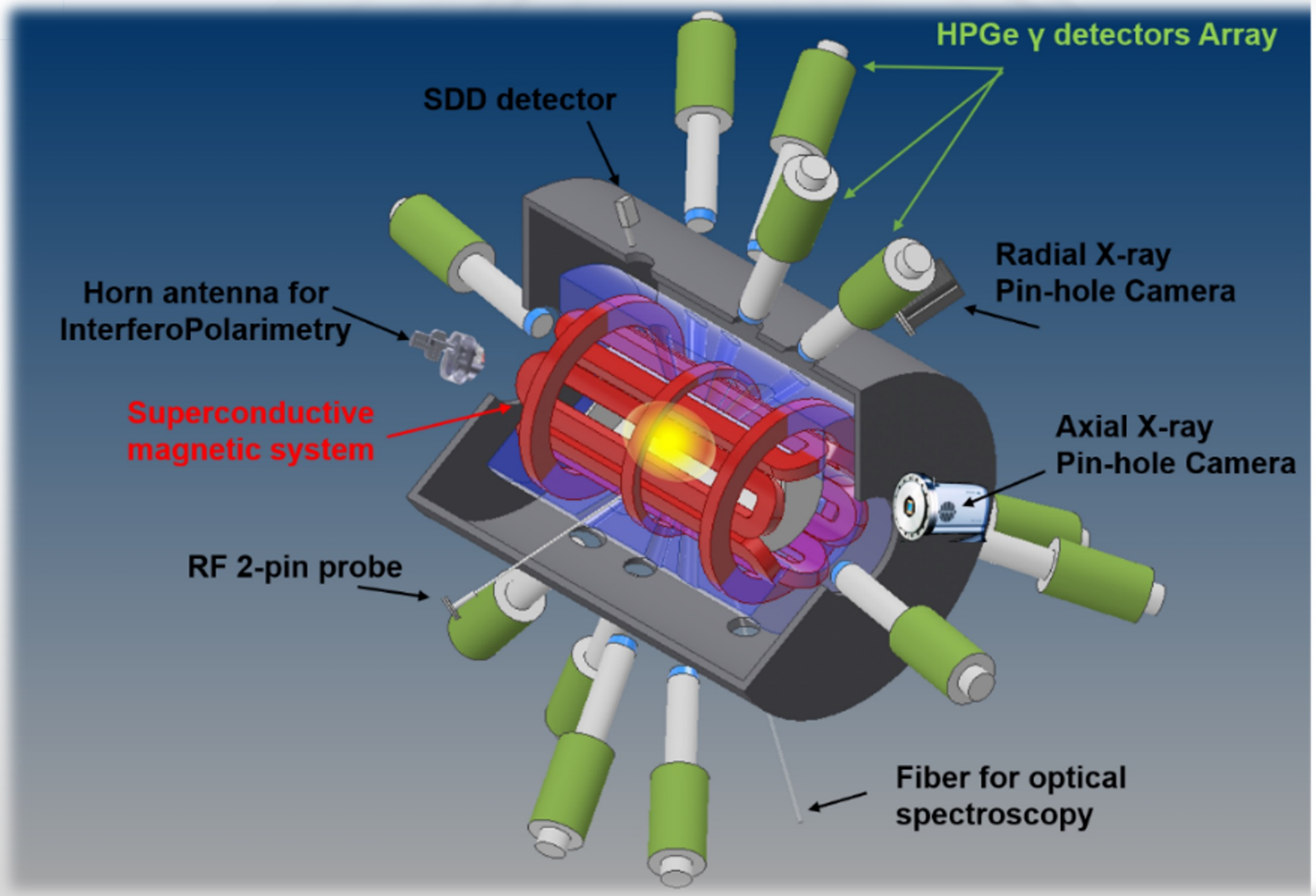




The PANDORA magnetic trap is composed of:

- 3 superconducting coils for axial confinement
- a superconducting hexapole for radial confinement

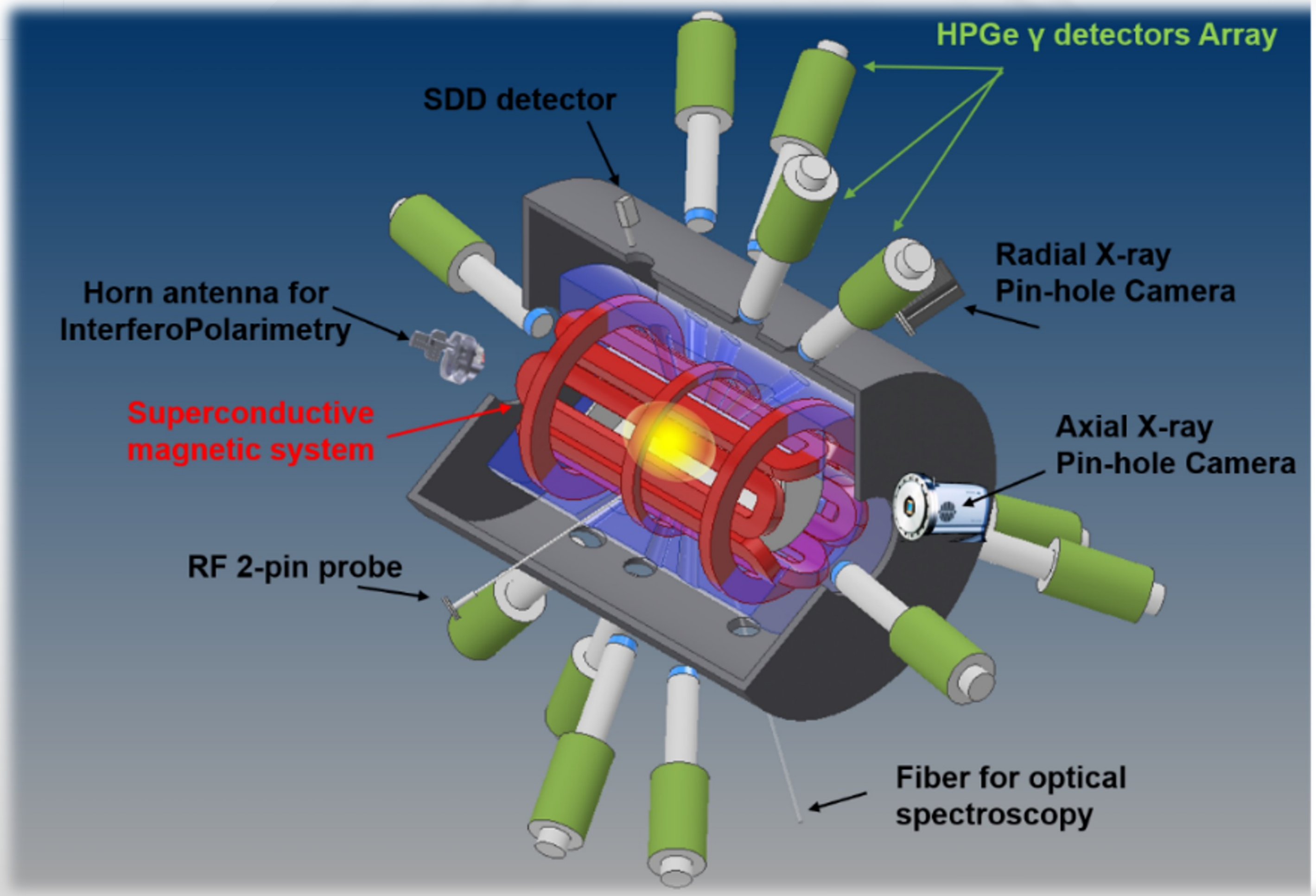
The PANDORA experiment

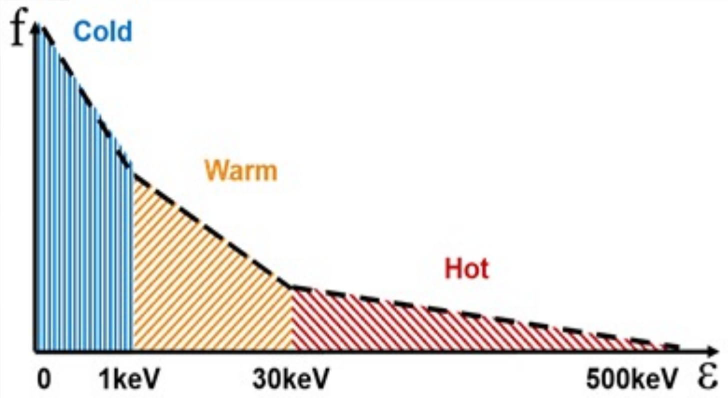


Array of **14 HPGe detectors** placed around the trap in correspondence to the holes in the magnetic system.

- HPGe use is mandatory due to their energy resolution
- Total photopeak detection efficiency simulated assuming an extended source (plasma volume of 1500 cm^3) $\sim 10^{-3}$
- Value of the order of 10^{-3} compensated by the large number of atoms in the plasma makes the measurements feasible
- No Anti-Compton Shields around HPGe
- Detectors will work in harsh experimental conditions (up 50 kHz on each detector) dedicated electronics able to run at high rate will be used
- No magnetic field effects on HPGe charge collection (detectors in a region B ~ 200 Gauss

The PANDORA experiment





Ionization states and charge state distributions are determined by the plasma temperature at a given density and assuming a certain confinement time → **plasma diagnostics** plays a relevant role in order to relate the plasma environment properties to the measured lifetimes

The PANDORA experiment

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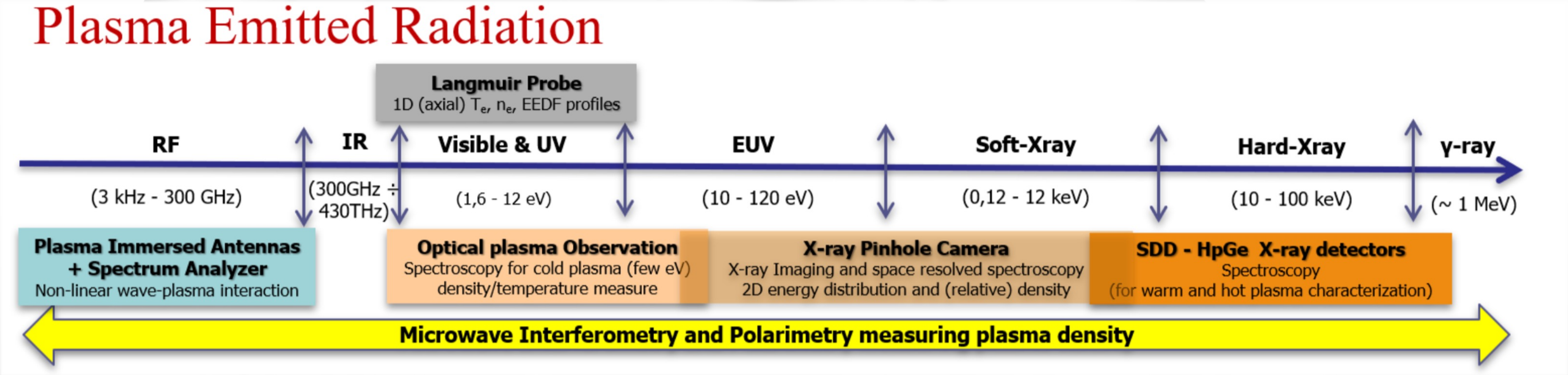


Eur. Phys. J. Plus (2023) 138:599
https://doi.org/10.1140/epjp/s13360-023-04157-0

The PANDORA experiment

The collaboration with theoreticians allowed to identify of a long list of isotopes (more than 100) of potential interest for stellar nucleosynthesis.

Three cases to be studied during the first measurement campaign:

Isotope	$T_{1/2}$ [yr]	E_γ [keV]
^{176}Lu	$3.78 \cdot 10^{10}$	202.88 & 306.78
^{134}Cs	2.06	795.86
^{94}Nb	$2.03 \cdot 10^{4}$	871.09

^{176}Lu physics case

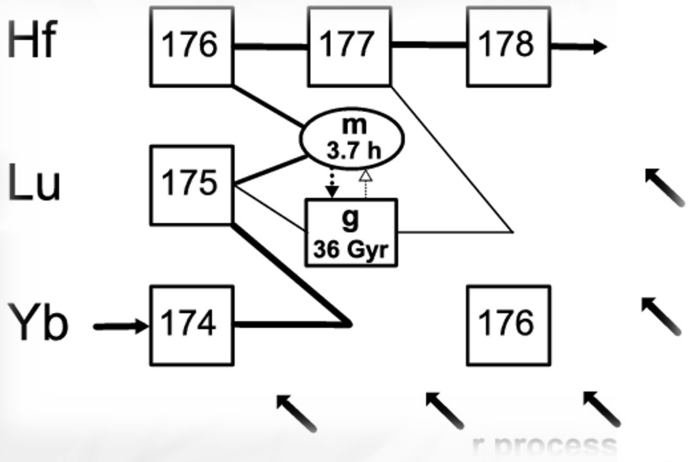
CSN3 Fisica Nucleare

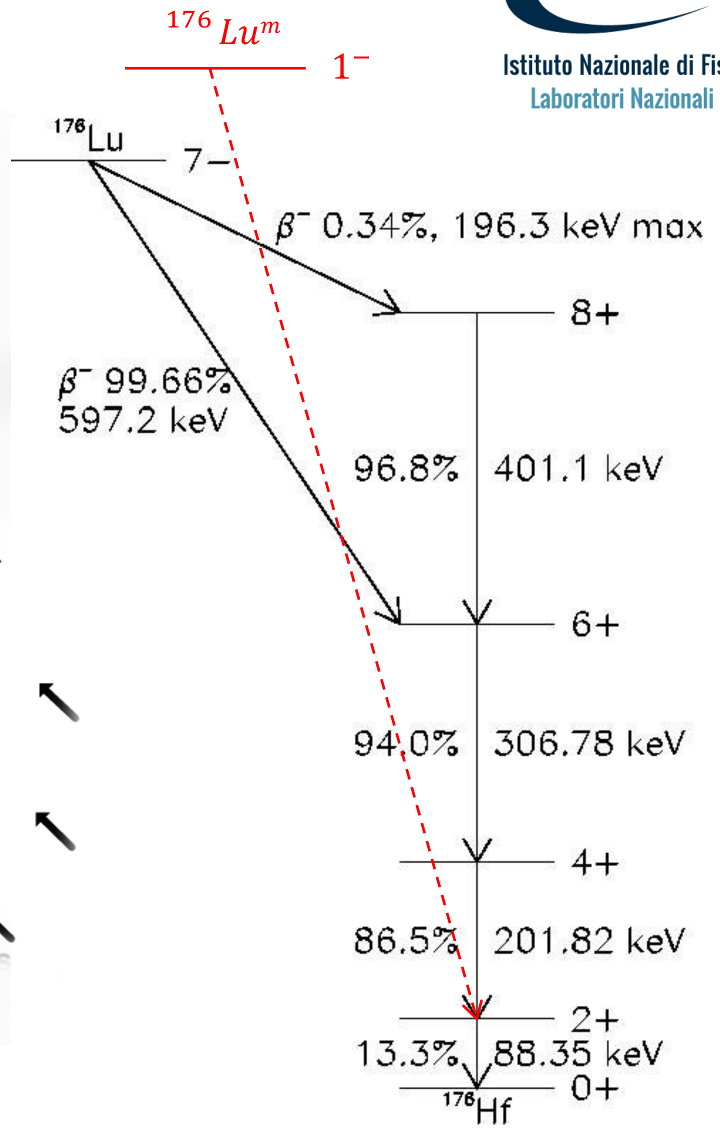
^{176}Lu physics case

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

^{176}Lu: is a very long-lived isotope in laboratory conditions and **in principle might act as a cosmo-chronometer**

- **the s-process branching point at ^{176}Lu is among the most important ones** for the understanding of slow neutron captures in the Asymptotic Giant Branch (AGB) phases of low and intermediate mass stars;
- **it determines the abundance of ^{176}Hf, an "s-only" nucleus**
- Scenario is complex due to the presence of an isomeric state placed at 122.45 keV with a very short lifetime





Important to investigate the *in-plasma* variations of the half-life

How to measure ^{176}Lu $t_{1/2}$ in plasma?

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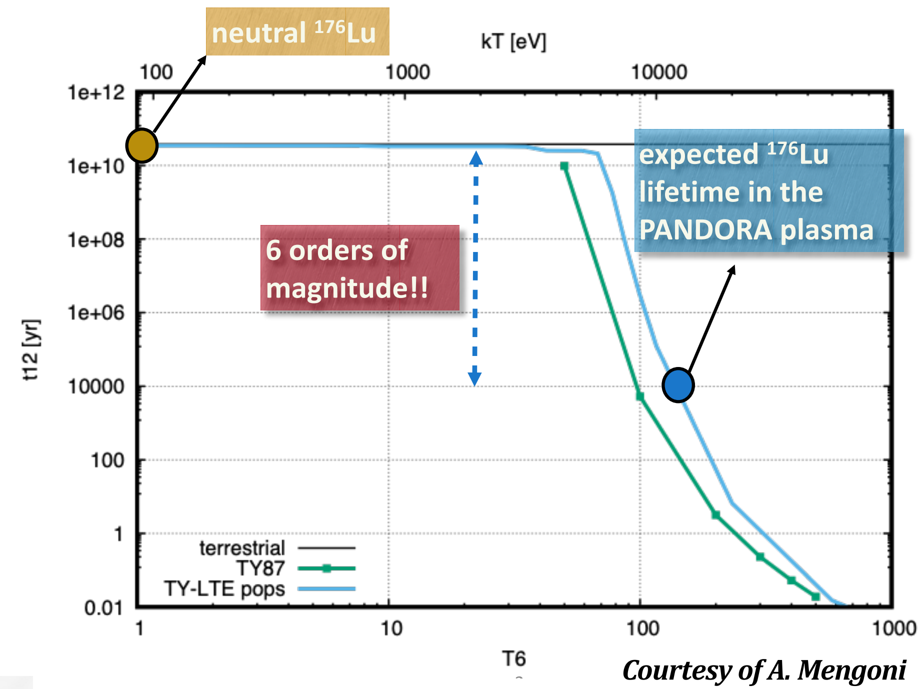
The PANDORA experiment

Build a plasma trap where ion species are confined in a magnetic field and a plasma is created with:

- **Electron density: $10^{12} \div 10^{14}\ cm^{-3}$**
- **Electron temperature: 0.1 ÷ 100 keV**
- **Ion density: $10^{11}\ cm^{-3}$ → relies on the radiactive isotope concentration in plasma**
- **Ion temperature: ~ 1 eV → Ions are cold: no access to the excited states**

^{176}Lu: lifetime vs. T – theoretical predictions



Courtesy of A. Mengoni

Takahashi et al. 1987, Phys Rev C 36, 1522

PANDORA: only ground state will be studied → T too low to investigate variation on the isomeric state

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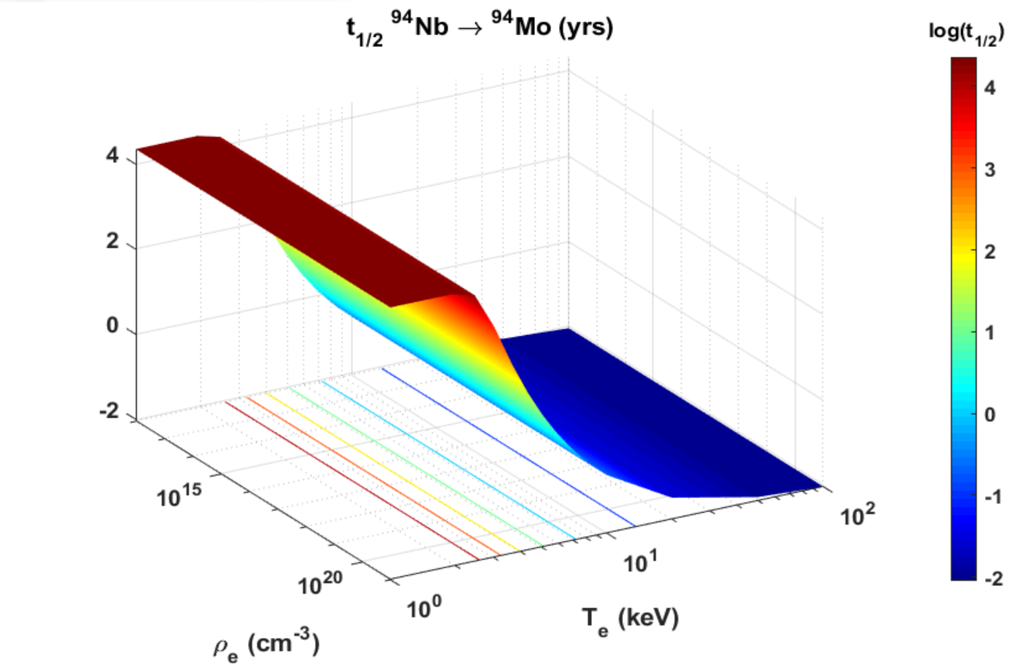

Variation with T_e stronger than with ρ_e → "stellar effect" can be modelled by ECR (*Electron CyclotronResonance*) plasma

How to measure ^{176}Lu $t_{1/2}$ in plasma?

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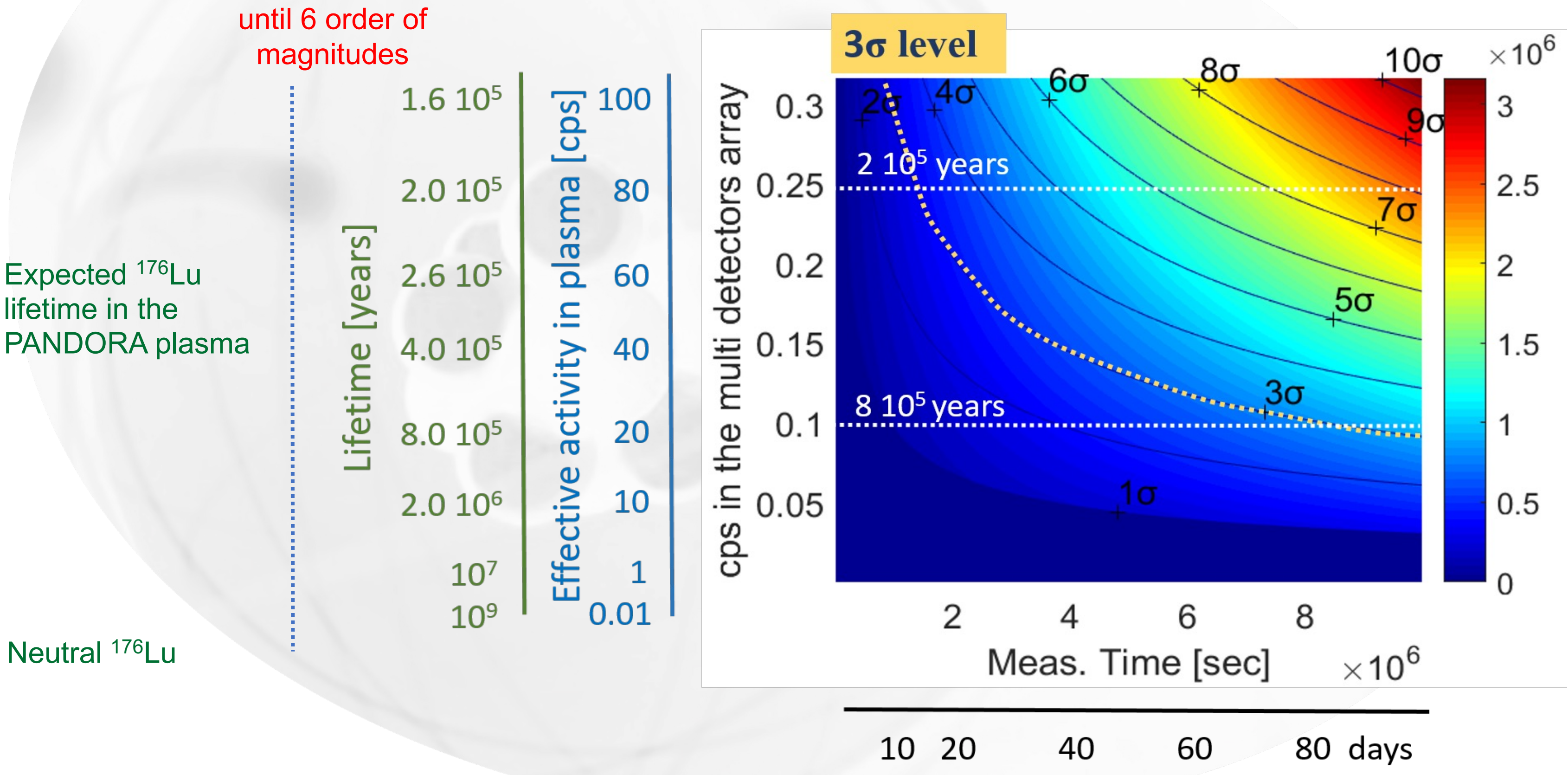

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Why to use laser-induced plasma

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How can we populate the 1^- isomeric level?

Using a laser-plasma as a source of polychromatic high energy X-ray photon flux one could simultaneously investigate isomeric photoactivation as well as in-plasma decay rate modification of ground and isomer levels

Thermalization between the ground and isomer levels may occur

The laser-plasma can be expected to produce X-ray spectra similar to the stellar interior, which can answer the question of equilibration more accurately than previous experiments on this topic!

Why to use laser-induced plasma

Magnetic confinement

PRO:

- **Long-living plasma** (order of weeks)
- Steady state dynamical equilibrium for density and temperature (by compensating ion losses)
- Hence, over days/weeks constant values for charge state distribution of in-plasma ions
- Online monitoring of plasma density, temperature, volume, at any energy domain in nLTE conditions

CONS:

- Low density/high temperature plasma: **nLTE conditions**
- Difficult "plasmization" of solid/metallic isotopes
- **No access to nuclear excited state studies** (too low T)

Laser-induced plasma

PRO:

- **High density plasma, reaching LTE**
- Fully thermodynamical equilibrium allows, in principle, to **estimate the population of nuclear excited states**

CONS:

- **Difficult to implement diagnostics** following on-time the fast time-variation of plasma parameters
- **Short living plasma**, with duration much shorter than typical lifetimes of isotopes involved in stellar nucleosynthesis

β-decay investigation in matter: from early experiments to storage rings

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In 1947 Segrè and Daudel pointed out that the **possibility to alter the decay rate of ^7Be by changing the electron density**, at least for low Z nuclei, an effect due to different chemical environment

PHYSICAL REVIEW VOLUME 71, NUMBER 4 FEBRUARY 15, 1947

Proceedings of the American Physical Society

MINUTES OF THE MEETING AT LOS ANGELES, CALIFORNIA, JANUARY 3–4, 1947

THE 276th meeting of the American Physical Society was held on Friday and Saturday, January third and fourth, 1947, at Los Angeles in Harris Hall of the University of Southern California. This was our first meeting at that University, which furnished excellent accommodations and management for our sessions. Our thanks are due particularly to R. E. Vollrath and G. L. Weissler. The attendance at the most populous session amounted to some 200. The four invited papers were admirable in content and presentation. The vice president of the Society was prevented by the grounding of his plane from presiding at the session of invited papers, and was replaced as Chairman by C. S. Van Atta. The other Chairmen were R. E. Vollrath and J. Kaplan.

J. KAPLAN
Local Secretary for the Pacific Coast
University of California
Los Angeles, California

While today…

A3. Possibility of Altering the Decay Rate of a Radioactive Substance. EMILIO SEGRÈ, *University of California, Berkeley*.—The radioactive decay constant of a substance decaying by orbital electron capture is proportional to $|\psi(0)|^2$ of the electrons. In the case of a light element like Be^7 it may be possible to alter this quantity by an appreciable amount by putting the Be in different chemical compounds. We would then have a slight change of the radioactive half-life of the Be in different compounds. The magnitude of the effect may be in the neighborhood of one percent, ~~but it is practically impossible to give a quantitative estimate~~ because the total change of $\psi(0)$ is affected by certain factors such as the density of the crystal, nature of the chemical bond, etc. They are both positive and negative, and have comparable magnitudes. To obtain a reliable estimate of the effect we require a more detailed knowledge of the wave functions for various compounds than is at present available. Experiments are in progress to detect the effect by comparing the half-life of Be^7 in Be metal with that in BeO or BeF_2.

backup

Storage ring experiments

1. The beta decay in highly ionized atoms shows important variations compared to neutral species

- *Electron Capture becomes impossible in fully ionized atoms.*
- *Bound state beta decay typically marginal can become important.*

2. Bare $^{163}Dy^{66+}$ nuclei, **being stable as neutral atoms, become radioactive**, thus allowing the s process, with a half-life of 33 days.

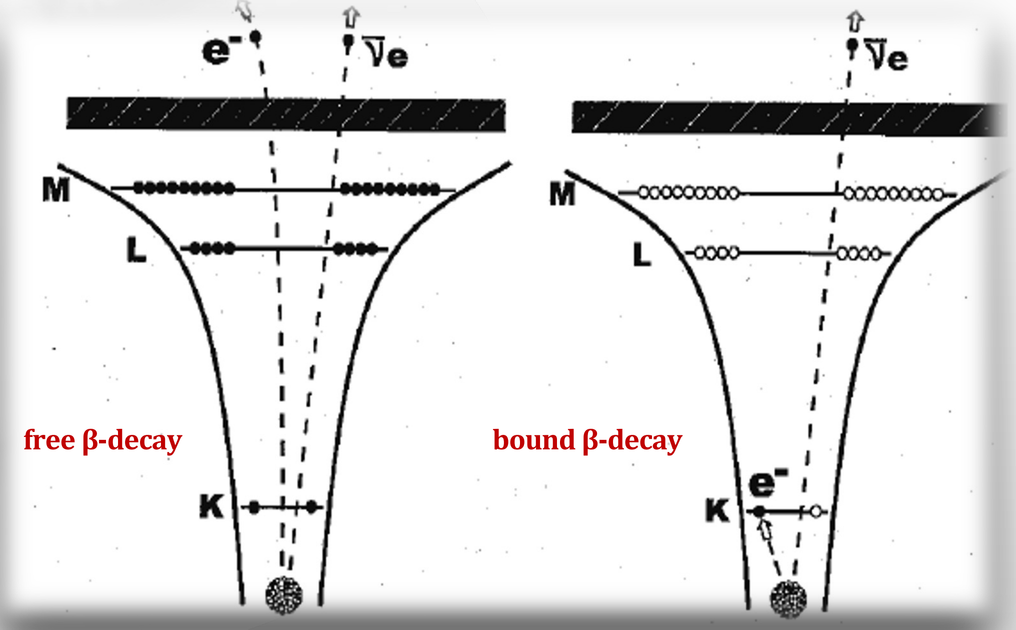
   M. Jung at al., First observation of bound-state β⁻ decay, Phys. Rev. Lett. 69, 1992

3. **Bare $^{187}Re^{75+}$ 187Re75+ ions decay, due to the bound-state beta decay, becomes 9 orders of magnitude faster than neutral ^{187}Re** atoms with a half-life of 42 Gyr.

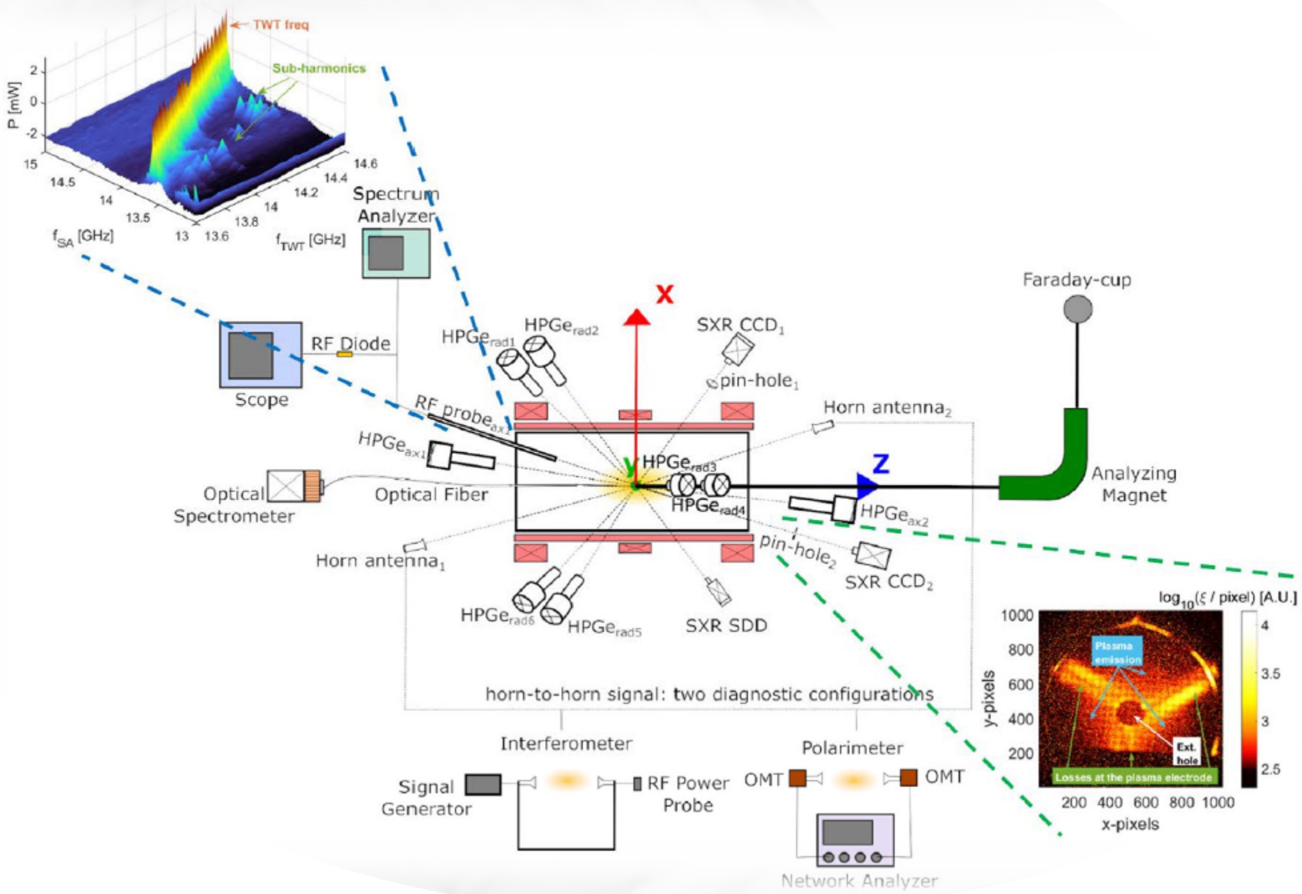
   F. Bosch at al., Observation of Bound-State β⁻ Decay of Fully Ionized ^{187}Re: ^{187}Re–^{187}Os Cosmochronometry, Phys. Rev. Lett. 77, 1996

4. $^{140}Pr^{58+}$ ions half-life T1/2 = 3.04 min (with a single orbital electron) due to EC decay is shorter than the one of $^{140}Pr^{0+}$ neutral ions with 59 electrons T1/2 = 3.39 min

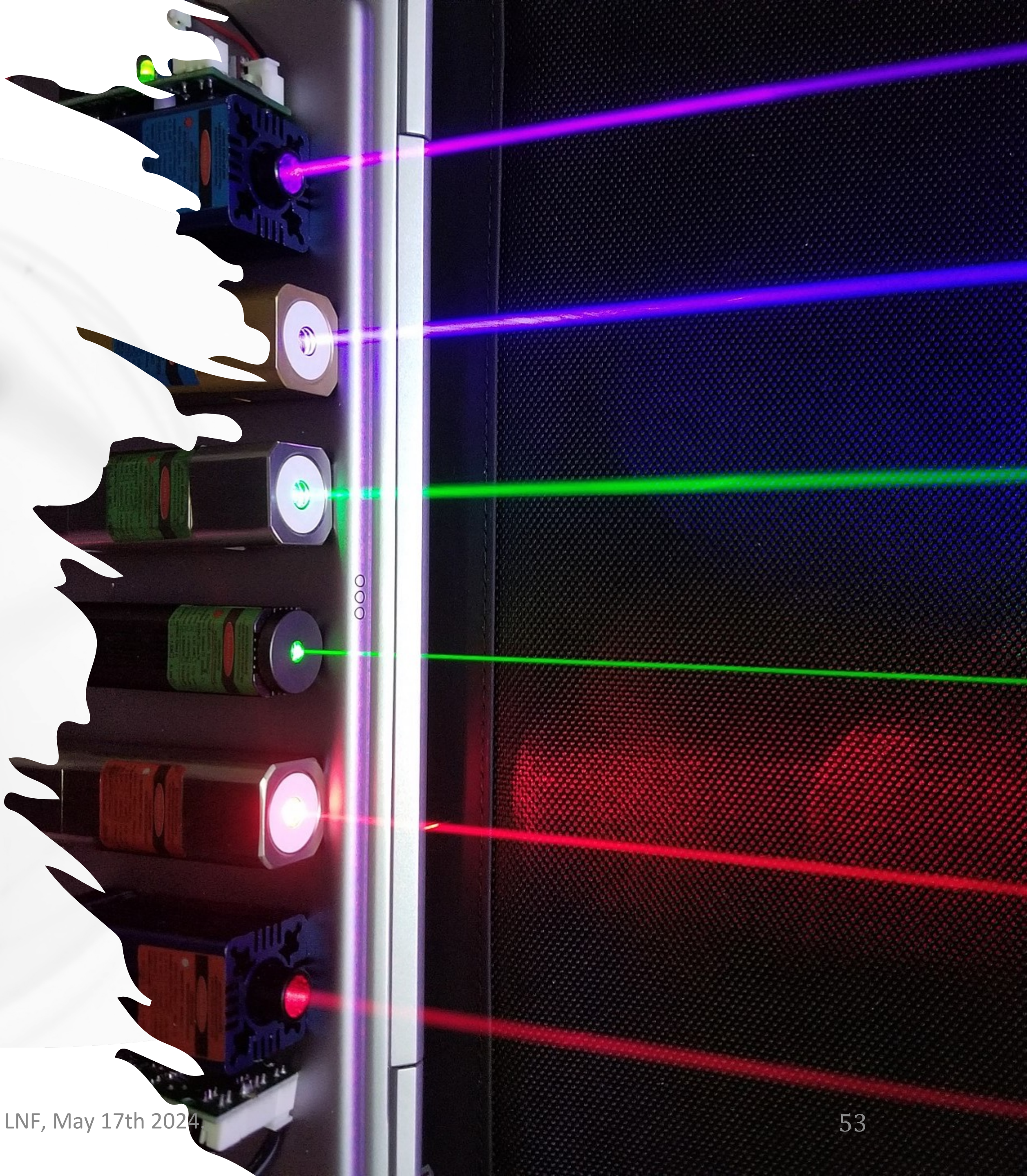
   Y. Litvinov et al., Measurement of the b+ and orbital electron capture decay rates in fully ionized, hydrogen-like and helium-like ^{140}Pr Ions Phys. Rev. Lett. 99, 2007, 262501



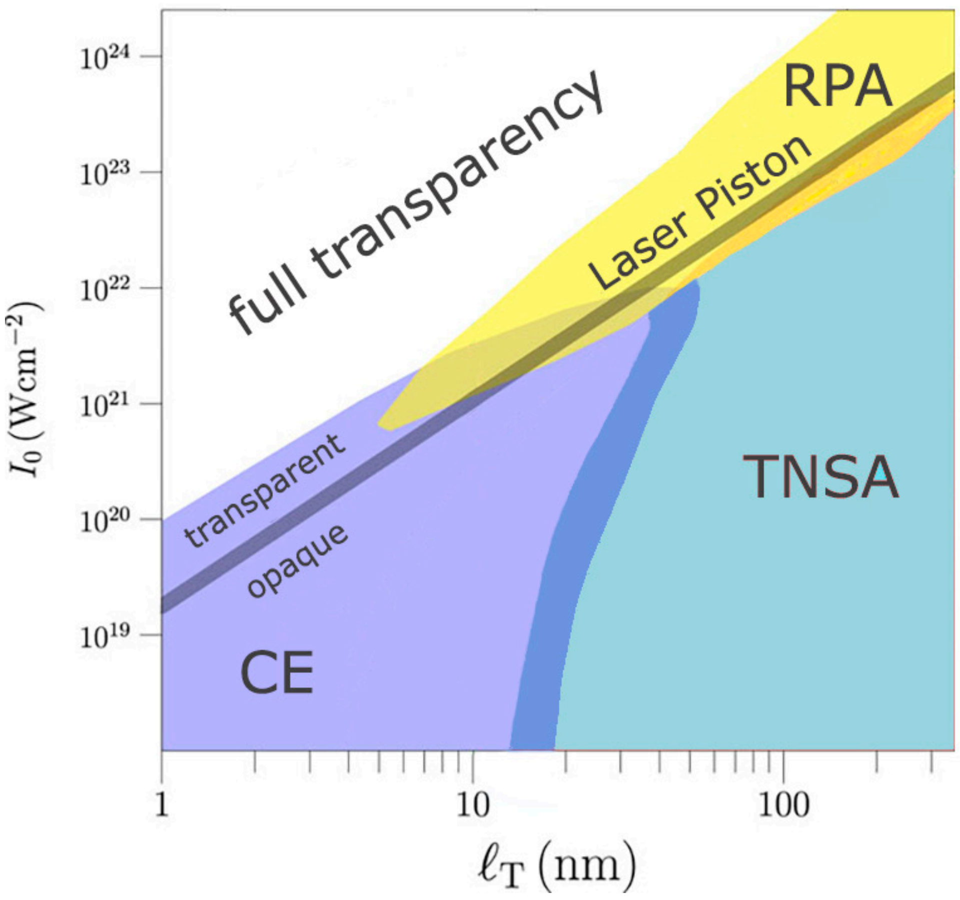
Y. Litvinov and F. Bosh: Rep. Prog. Phys. 74, 016301 (2011)


TWT freq
Sub-harmonics
P [mW]
f_{SA} [GHz]
f_{TWT} [GHz]
Spectrum Analyzer
RF Diode
Scope
RF probe$_{ax1}$
$HPGe_{rad1}$
$HPGe_{rad2}$
SXR CCD_1
pin-hole$_1$
Horn antenna$_2$
Faraday-cup
$HPGe_{ax1}$
Optical Spectrometer
Optical Fiber
$HPGe_{rad3}$
$HPGe_{rad4}$
$HPGe_{ax2}$
Analyzing Magnet
pin-hole$_2$
SXR CCD_2
Horn antenna$_1$
$HPGe_{rad6}$
$HPGe_{rad5}$
SXR SDD
horn-to-horn signal: two diagnostic configurations
Interferometer
Polarimeter
Signal Generator
RF Power Probe
OMT
OMT
Network Analyzer
$log_{10}(\xi$ / pixel) [A.U.]
y-pixels
x-pixels
Plasma emission
Ext. hole
Losses at the plasma electrode

Why laser



Laser-matter interaction

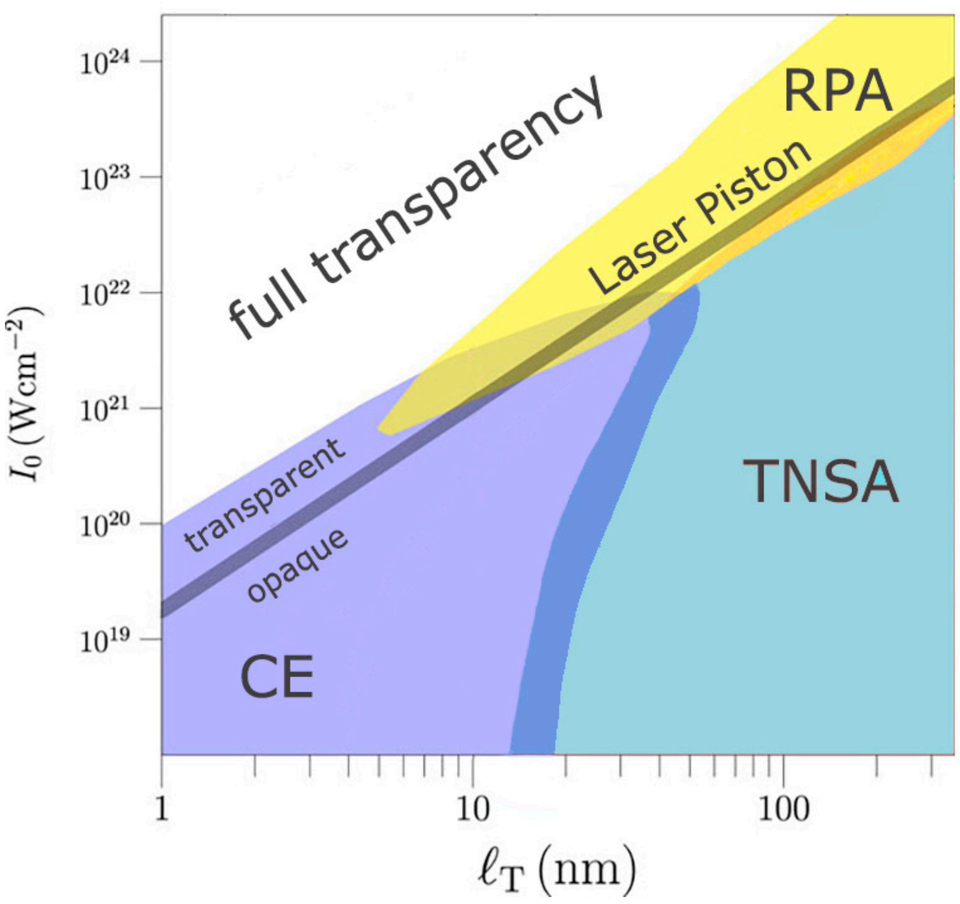


When a high intensity laser pulse (above 10^{18} W/cm^2) is focused in a spot of the order of a few microns on a target placed in vacuum, a plasma consisting of electrons and ions is created almost instantaneously.

- **Target Normal Sheath Acceleration (TNSA):** effective in accelerating protons and light ions → a short laser pulse interacting with the target front surface produces a plasma made of ions and fast electrons.

- **Coulomb Explosion (CE):** optimized for clustered gaseous targets, intensities in the range $10^{18} \div 10^{20}$ W/cm^2 and τ < 200 fs → an explosion may occur due to the intense laser field that, extricating several electrons from the molecule cluster, induces a high level of ionization. Possible also for thin (1-10 nm), solid targets or nano-structured targets

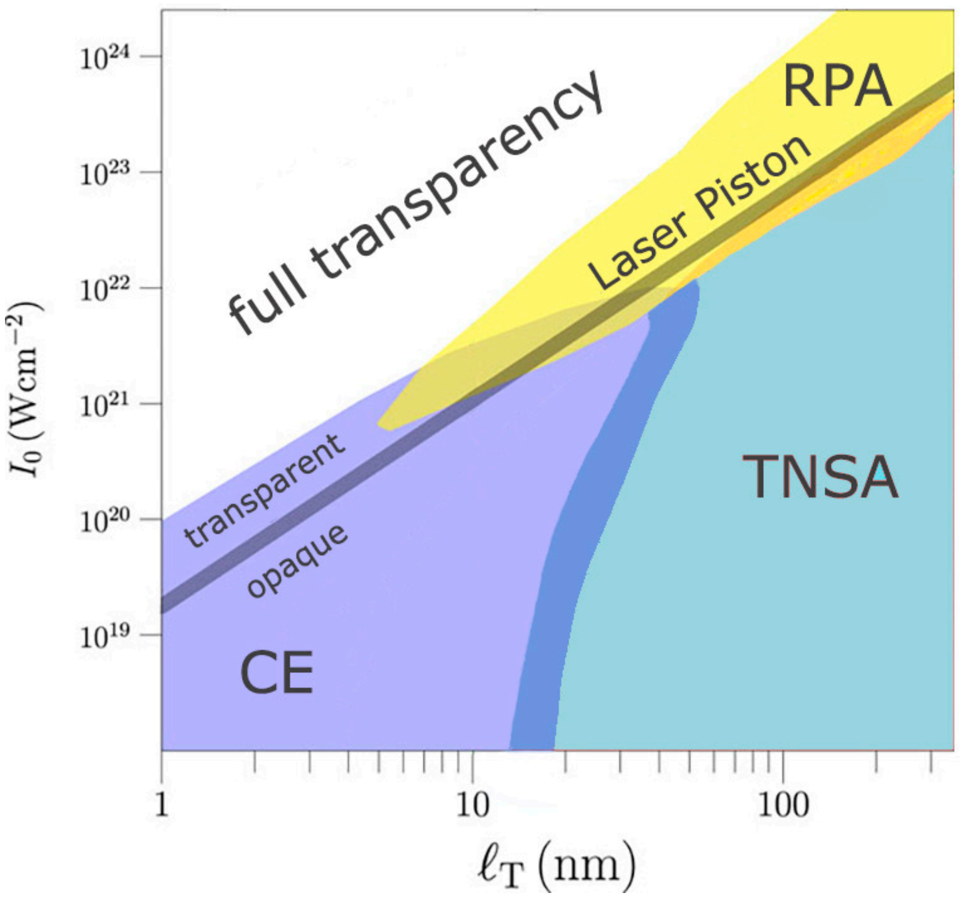
Laser-matter interaction



When a high intensity laser pulse (above 10^{18} W/cm^2) is focused in a spot of the order of a few microns on a target placed in vacuum, a plasma consisting of electrons and ions is created almost instantaneously.

- **Radiation Pressure Acceleration (RPA), or Laser Piston regime:** based on the action of the radiation pressure induced in the interaction of a short laser pulse, of extremely high intensity (above $10^{20} \div 10^{21}$ W/cm^2), with a thin and dense pre-plasma layer created, in front of a target, by the laser-pulse leading edge. The plasma electrons are locally separated from the plasma ions creating a strong accelerating field which efficiently accelerates the ions in the irradiated target area.

Laser-matter interaction



A precise control of the experimental conditions is challenging with high-power lasers → variations observed between experiments performed in conditions which would seem similar at a first glance.

The scaling of the most important characteristics (such as the energy per particle) with laser and target parameters is still unclear to a large extent, despite the large number of investigations performed.

Why to use laser-induced plasma

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- **Ion temperature: ~ 1 e → Ions are cold: no access to the excited states**

$$\frac{dN}{dt} = \lambda n_i V \rightarrow \int_0^{T_{meas}} dN = \int_0^{T_{meas}} \lambda n_i V\ dN$$

$$\mathrm{N}(T_{meas}) = \lambda n_i V T_{meas}$$

Why to use laser-induced plasma

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Exploring the onset of a (Full) Local Thermal Equilibrium:

- Typical lifetime of nuclear excited states ~ 10^{-15} s
- Assuming an excited state for, *e.g.*, ^{176}Lu*, around 122.45 keV
- Considering n_e=<q>n_i= $10^{27}\ m^{-3}$ (a typical stars interior density), at T_e=T_i=6.68 keV, the excited level lifetime is already exactly the same of the excitation rate, meaning **that this level can be populated and it is in thermal equilibrium in the assumed laser-induced plasma lifetime** (order of ps or tens of ps)
- Calculation also rescaled to a more realistic expected density of a real laser-induced plasma scenario (n=e=n_i= $10^{25}\ m^{-3}$) → the required plasma temperature to get the thermal equilibrium goes to around 37.5 keV. **This value seems to be however absolutely achievable in the foreseen laboratory scenario, confirming that the decay from excited states is in principle feasible.**

Simulations by B. Mishra et al.: thanks, Bharat!

How to create and confine plasma

How to make it stable?

The ideal confinement requires some **stringent conditions on plasma equilibrium and stability**.

Plasma can also be viewed as a fluid:

$$p_{kin} = \Sigma nkT$$

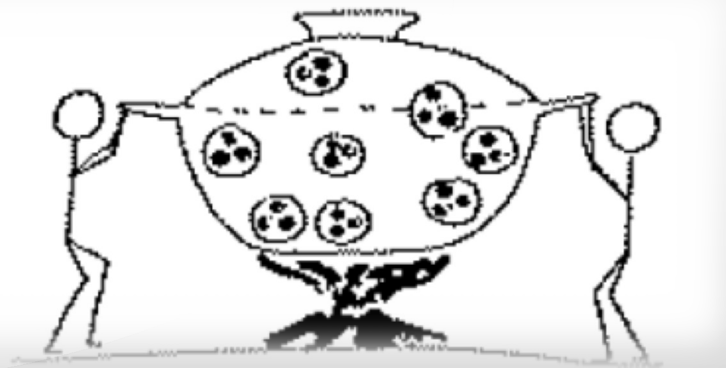
$$p_{mag} = {B^2}/{2\mu_0}$$

The stability of the confinement can be studied as a function of the β parameter which is the ratio between kinetic and magnetic pressure

$$\beta = \frac{\Sigma nkT}{{B^2}/{2\mu_0}}$$

The condition for a magnetically stable plasma is $\boldsymbol{\beta} \ll 1$

B)



β-decay investigation in matter: from early experiments to storage rings

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1. Long standing question: How constant really are nuclear decay constant?

   One of the paradigms of nuclear science since the very early days has been the general understanding that the decay constant is independent of extranuclear considerations

2. What happens to β-radioisotopes under extreme conditions of Temperature (2500 K), Pressure (2000 atm) or Magnetic fields (80000 G)?

   Almost nothing… < 0.05 % decay constant variation

   G. T. Emery, Perturbation of Nuclear Decay Rates, Annual Review of Nuclear Science 22
   H. Mazaki et al., Effect of Pressure on the Decay Constant of ^{99m}Tc, Phyc. Rev. C 5, 1972 1972

3. In 1947 Segrè and Daudel pointed out that the possibility to alter the decay rate of 7Be by changing the electron density, at least for low Z nuclei, an effect due to different chemical environment

   E. Segrè, Possibility of altering the decay rate of a radioactive substance Phys. Rev. 71, (274) 1947

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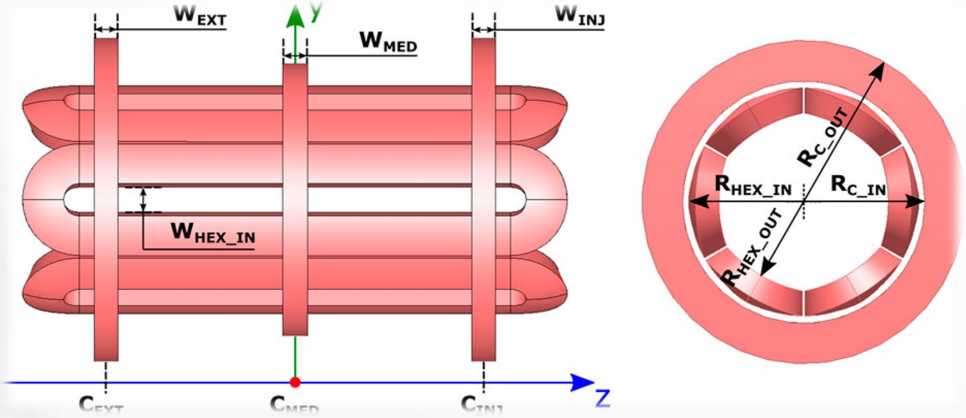
4. How does the surrounding chemical environment (lattice structure and electron affinity) affect the host atoms decay? $(e.g.\ \ ^7Be \rightarrow\ ^7Li)$

   A variation of E.C. lifetime of around 3.5%

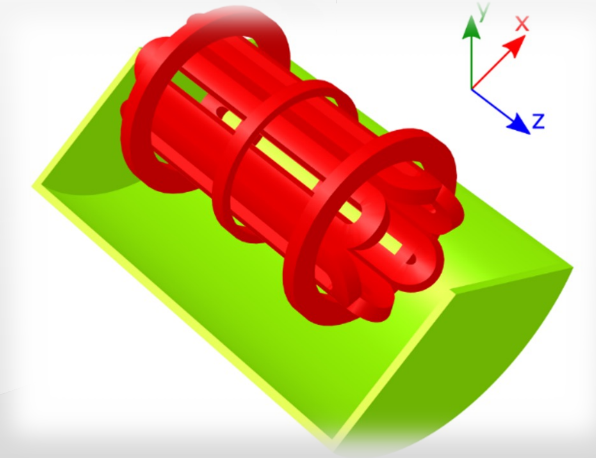
PANDORA magnetic system

The PANDORA's trap has been designed to operate at 18 + 21 GHz.

The magnetic system will have a length **L = 700 mm** and a radius **R = 300 mm.**
It will enclose a plasma chamber with inner radius **R_{CH_IN} = 140 mm** and length **L = 700 mm**.
The SC coils and hexapole will be made of **Niobium-Titanium alloy (NbTi)**, whose upper critical field is about 10 T at 4.2 K.



G. Mauro et al. - Front. Phys. 10:931953 (2022)



MAGNETIC SYSTEM FIELD REQUIREMENTS	
B_{inj} max @ z = -350 mm	3 T
B_{inj} operative range	1.7 T – 3 T
B_{ext} max @ z = 350 mm	3 T
B_{ext} operative range	1.7 T – 3 T
B_{min} @ z = 0 mm	0.4 T
B_{hex} @ R_{CH_IN} = 140 mm	1.6 T
LHe	Free
Warm Bore radius	150.5 mm

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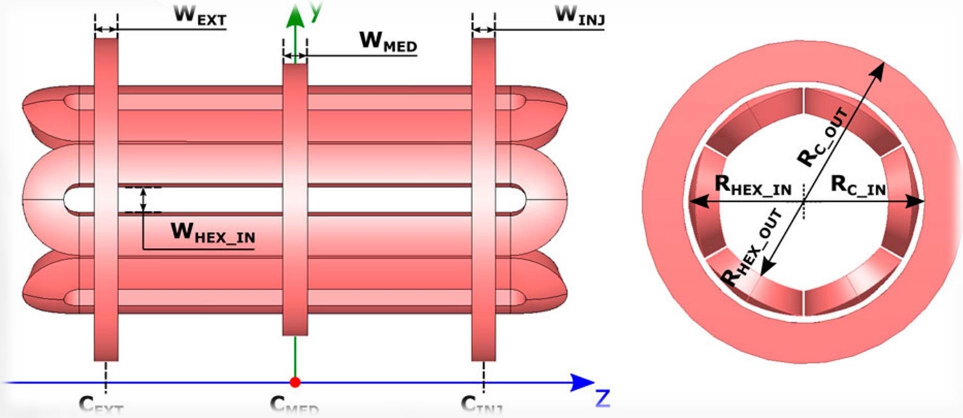

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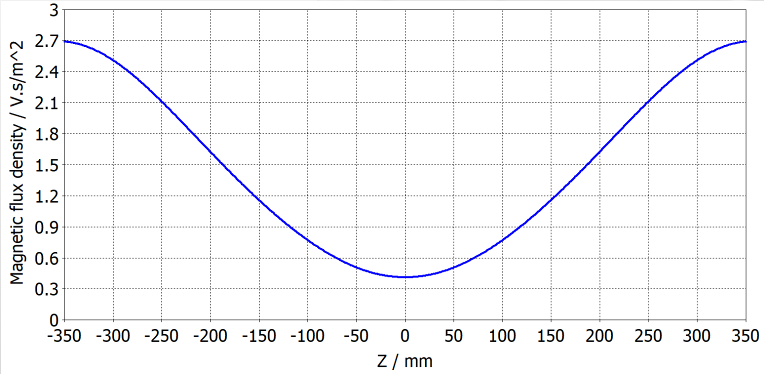
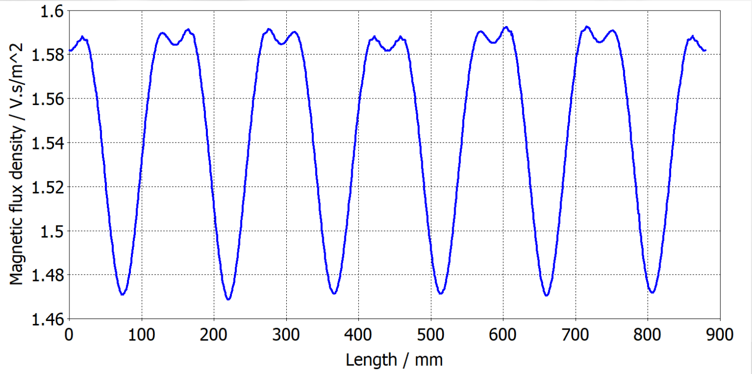
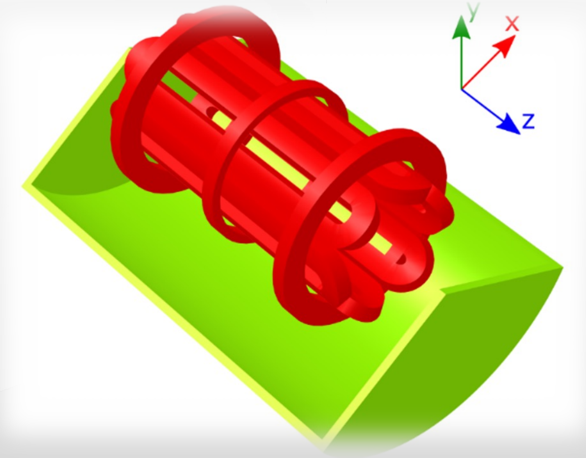


Axial magnetic field profile



Radial magnetic field profile



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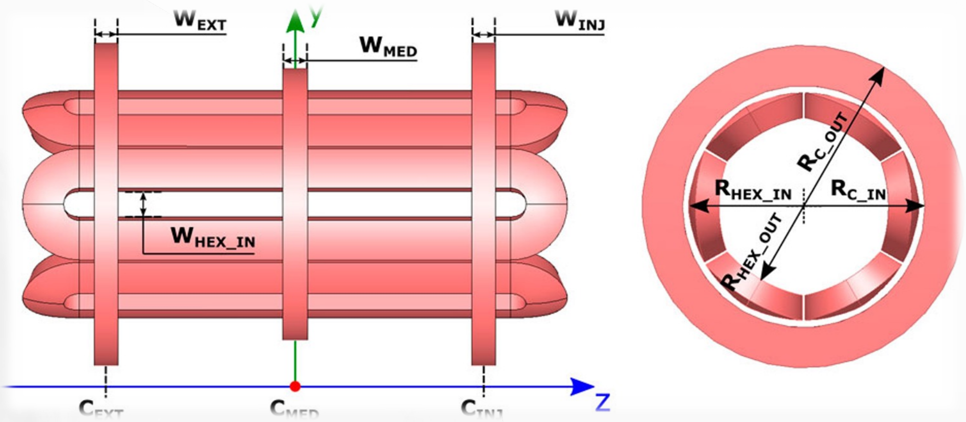

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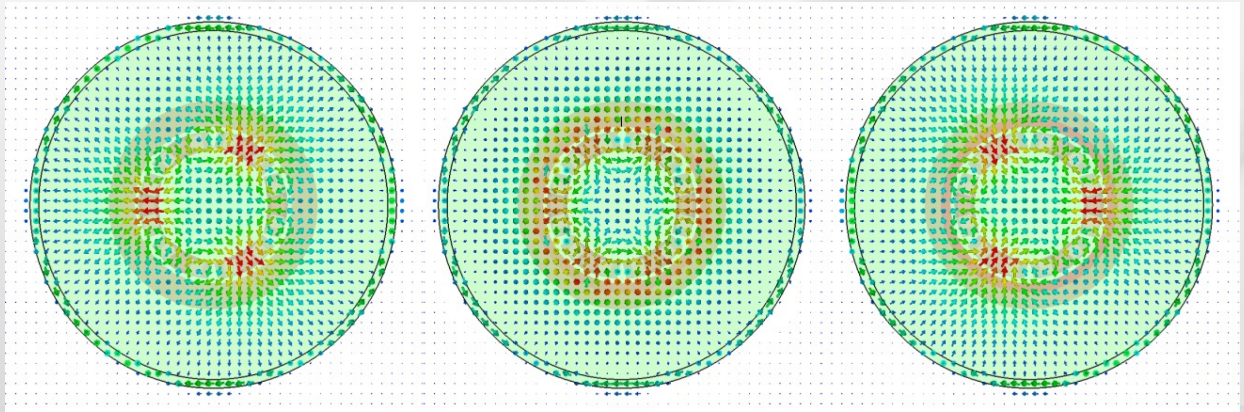
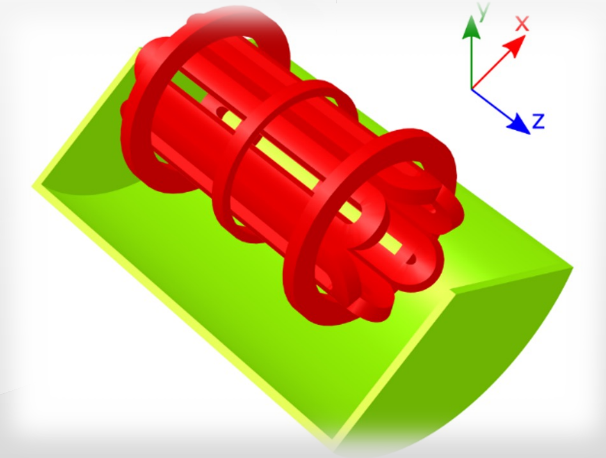
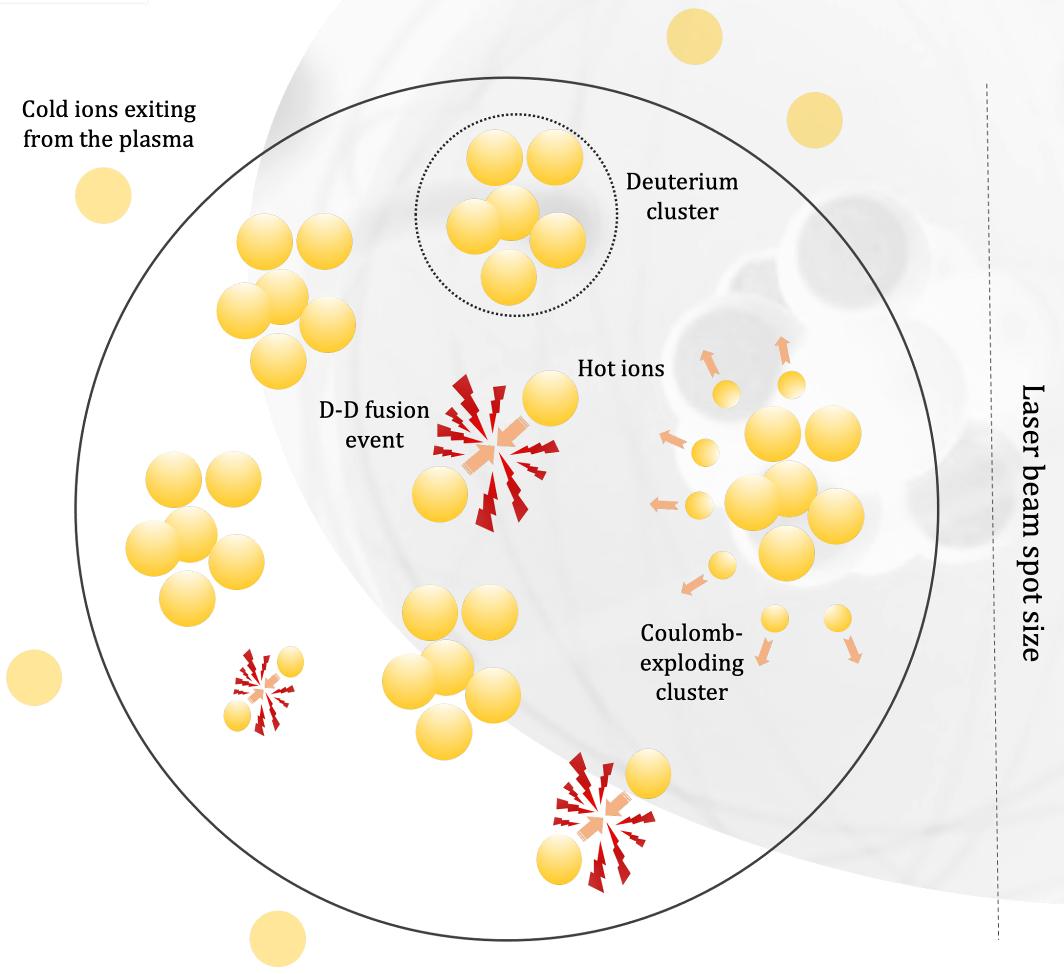




Deuterium fusion process in plasma



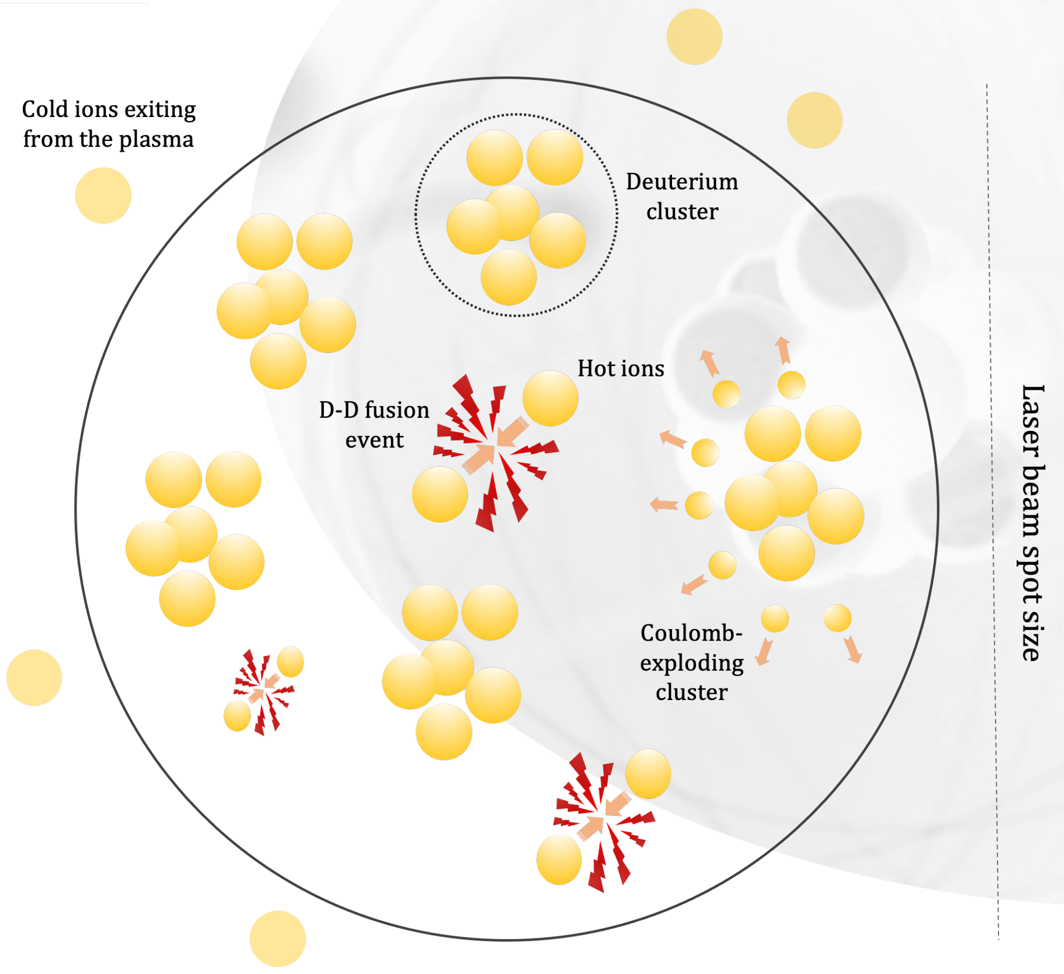
$$d + d \rightarrow {}^{3}He + \mathrm{n}\ (2.45\ \mathrm{MeV})$$

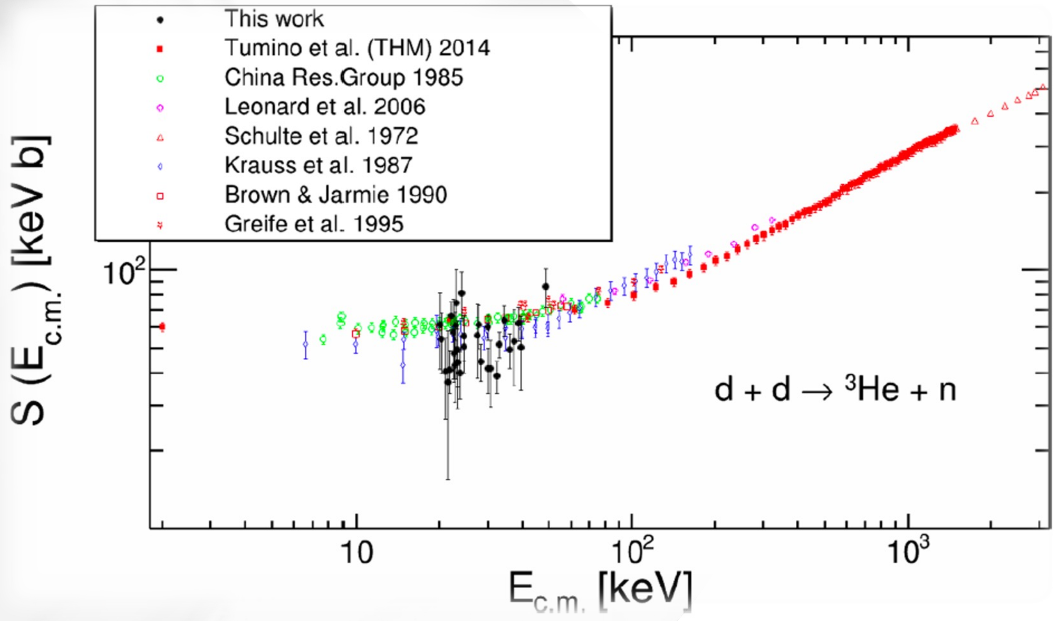
It is a nuclear fusion reaction crucial for understanding early phases of **Nucleosynthesis**

It took place right after the hadronization step was over, when there were free p and n that eventually combine to form deuterium.

Indirect measurements of the deuterium burning available (1.5 MeV ÷ 2 keV), also exploiting the so-called Trojan-Horse Method. **However, a full comprehension of possible electron screening effects is crucial.**

Deuterium fusion process in plasma





Model-independent determination of the astrophysical S factor in laser-induced fusion plasmas

D. Lattuada, M. Barbarino, A. Bonasera, W. Bang, H. J. Quevedo, M. Warren, F. Consoli, R. De Angelis, P. Andreoli, S. Kimura, G. Dyer, A. C. Bernstein, K. Hagel, M. Barbui, K. Schmidt, E. Gaul, M. E. Donovan, J. B. Natowitz, and T. Ditmire

Phys. Rev. C **93**, 045808 – Published 19 April 2016

See talk by L. Guardo

^{176}Lu physics case

^{176}Lu: is a very long-lived in laboratory conditions and **in principle might act as a cosmo-chronometer**

- **the s-process branching point at ^{176}Lu is among the most important ones** for the understanding of slow neutron captures in the Asymptotic Giant Branch (AGB) phases of low and intermediate mass stars;
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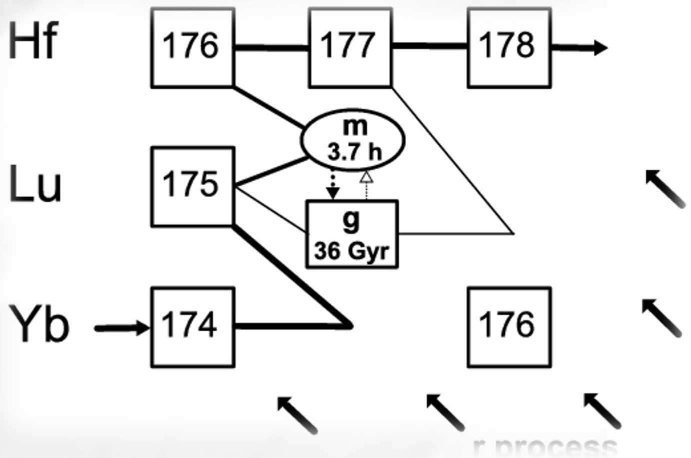

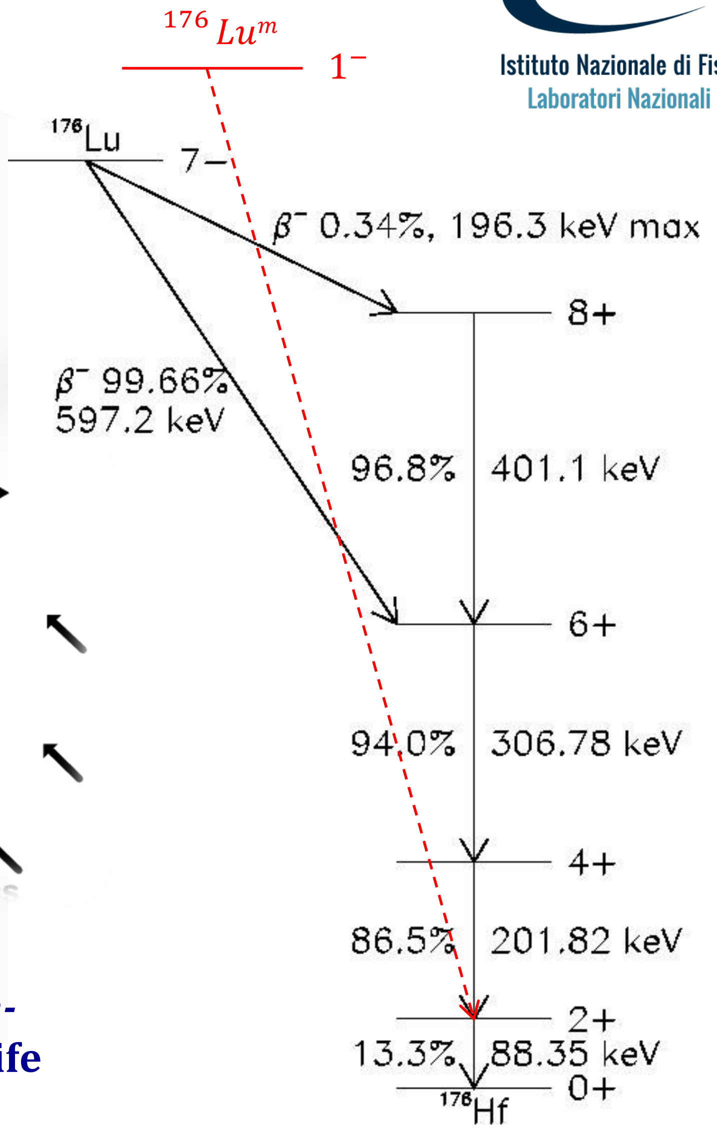

Important to investigate the *in-plasma* variations of the half-life

See talk and poster by B. Mishra

Why to use laser-induced plasma

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Laser-induced plasma

PRO:

- **High density plasma, reaching LTE**
- Fully thermodynamical equilibrium allows, in principle, to **estimate the population of nuclear excited states**

CONS:

- **Difficult to implement diagnostics** following on-time the fast time-variation of plasma parameters
- **Short living plasma**, with duration much shorter than typical lifetimes of isotopes involved in stellar nucleosynthesis

Nuclear physics: beta decays in plasma

How to measure ^{176}Lu $t_{1/2}$ in plasma?

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Scaling results to stellar environment

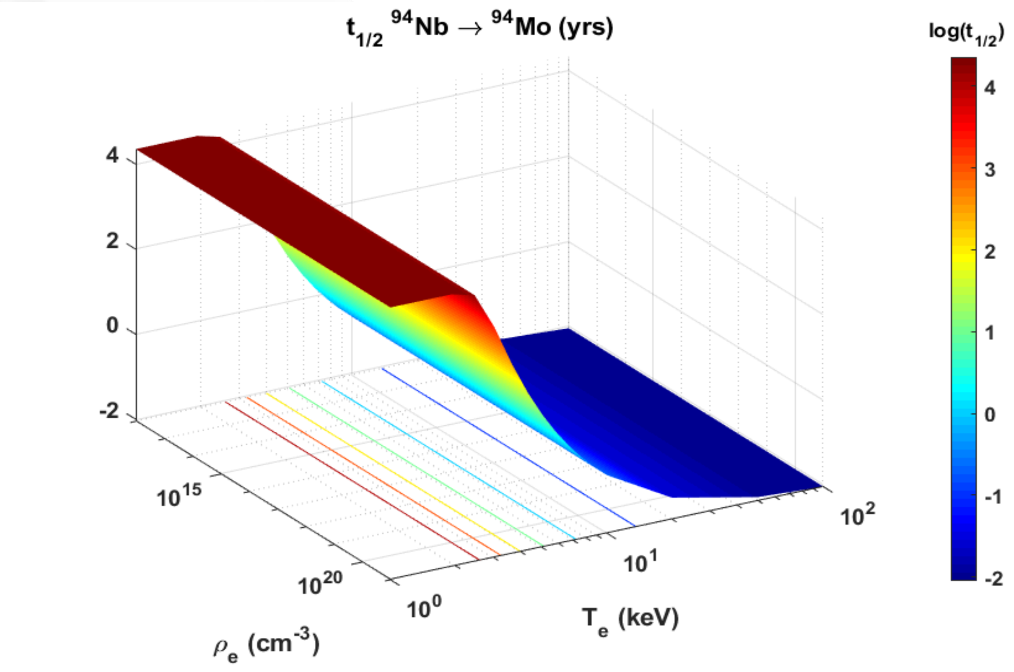
Build a plasma trap where ion species are confined in a magnetic field and a plasma is created with:

- **Electron density: $10^{12} \div 10^{14}\ cm^{-3}$**
- **Electron temperature: 0.1 ÷ 100 keV**
- **Ion density: $10^{11}\ cm^{-3}$ → relies on the radiactive isotope concentration in plasma**
- **Ion temperature: ~ 1 e → Ions are cold: no access to the excited states**

$$\frac{dN}{dt} = \lambda n_i V \rightarrow \int_0^{T_{meas}} dN = \int_0^{T_{meas}} \lambda n_i V\ dN$$

$$\mathrm{N}(T_{meas}) = \lambda n_i V T_{meas}$$

$n_i V$: density and plasma volume, constant → to be measured using multiple diagnostic tools



T_e = 0.1-100 keV in a lab. Magnetoplasma

Variation with T_e stronger than with ρ_e → "stellar effect" can be modelled by ECR (*Electron Cyclotron Resonance*) plasma

Why to use laser-induced plasma

How can we populate the 1^- isomeric level?

The intermixing depends on photoactivation rate λ^c of the nucleus through a bath of high energy X-ray photons obeying a Planck distribution in the thermal equilibrium stellar plasma.

Using a laser-plasma as a source of polychromatic high energy X-ray photon flux one could simultaneously investigate isomeric photoactivation as well as in-plasma decay rate modification of ground and isomer levels

The experimental methodology revolves around the measurement of two quantities:

- *photoactivation rate* $\lambda^c\,(n_e, n_i, T, s)$
- *decay rates* $\lambda^d\,(n_e, n_i, T, s)$ *from g.s. and isomeric states*

Thermalization between the ground and isomer levels occurs when:

$\lambda^c(n_e, n_i, T, s) >= \lambda_m^d\,(n_e, n_i, T, s)$
(*onset of equilibrium between the levels*)

See poster by B. Mishra

The laser-plasma can be expected to produce X-ray spectra similar to the stellar interior, which can answer the question of equilibration more accurately than previous experiments on this topic!

Why to use laser-induced plasma

Build a plasma trap where ion species are confined in a magnetic field and a plasma is created with:

- Electron density: $10^{12} \div 10^{14}\ cm^{-3}$
- Electron temperature: $0.1 \div 100$ keV
- Ion density: $10^{11}\ cm^{-3}$ → relies on the radiactive isotope concentration in plasma
- **Ion temperature: ~ 1 e → Ions are cold: no access to the excited states**

$$\frac{dN}{dt} = \lambda n_i V \rightarrow \int_0^{T_{meas}} dN = \int_0^{T_{meas}} \lambda n_i V\, dN$$

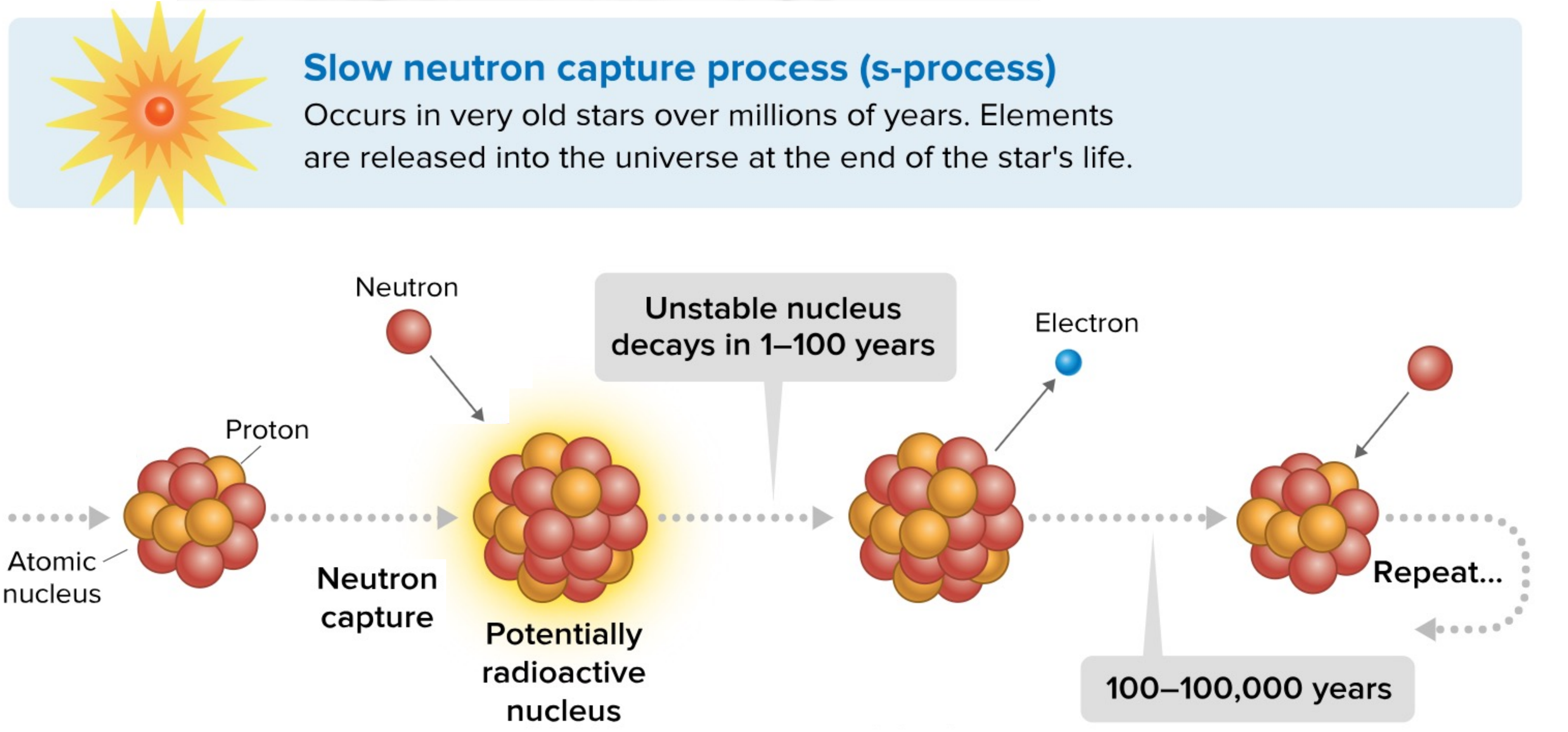
$$N(T_{meas}) = \lambda n_i V T_{meas}$$

Simulations by B. Mishra et al.

Exploring the onset of a (Full) Local Thermal Equilibrium:

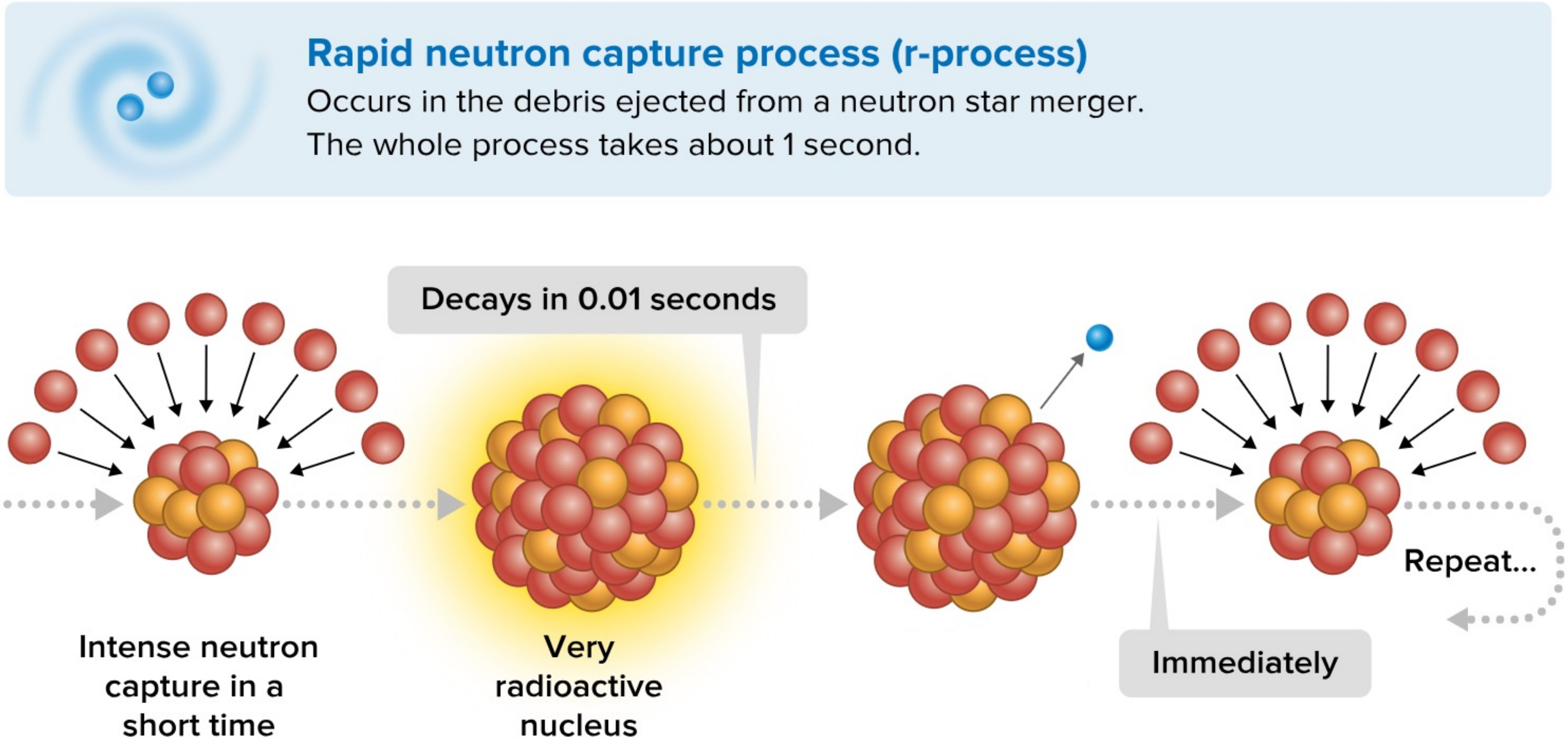
- Typical lifetime of nuclear excited states ~ 10^{-15} s
- Assuming an excited state for, *e.g.*, ^{176}Lu*, around 122.45 keV
- Considering n_e=<q>n_i= $10^{27}\ m^{-3}$ (a typical stars interior density), at T_e=T_i=6.68 keV, the excited level lifetime is already exactly the same of the excitation rate, meaning **that this level can be populated and it is in thermal equilibrium in the assumed laser-induced plasma lifetime** (order of ps or tens of ps)
- Calculation also rescaled to a more realistic expected density of a real laser-induced plasma scenario (n=e=n_i= $10^{25}\ m^{-3}$) → the required plasma temperature to get the thermal equilibrium goes to around 37.5 keV. **This value seems to be however absolutely achievable in the foreseen laboratory scenario, confirming that the decay from excited states is in principle feasible.**

Fusion processes: heavy elements



Picture from *https://knowablemagazine.org/article/physical-world/2018/crash-stars-reveals-origins-heavy-elements*

Fusion processes: heavy elements



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s-process endpoint

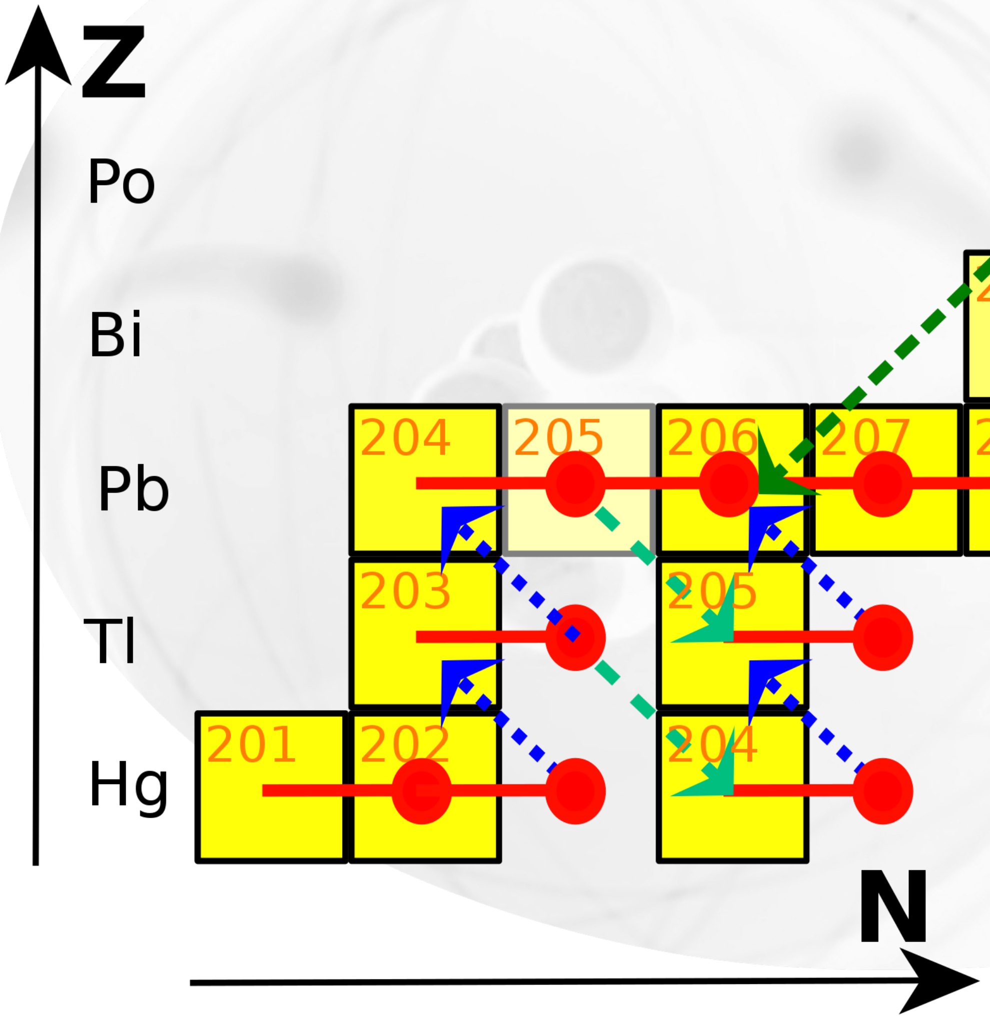
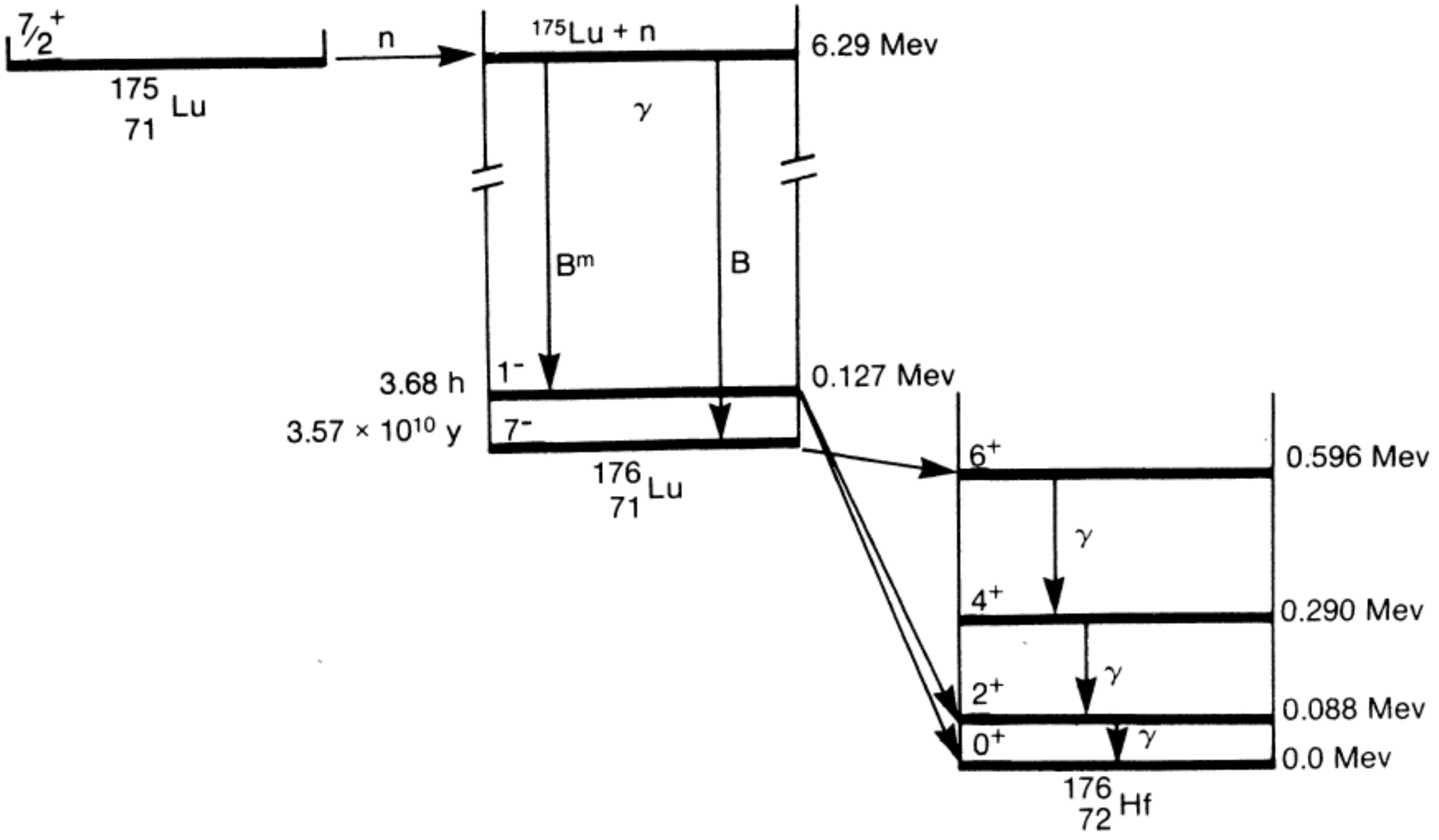


Chart representing the final part of the *s*-process. Red horizontal lines with a circle in their right ends represent neutron captures; blue arrows pointing up-left represent beta decays; green arrows pointing down-left represent alpha decays; cyan/light-green arrows pointing down-right represent electron captures.

Decay scheme for lutetium



^{176}Lu physics case

Cosmo-chronometer or stellar thermometer?

^{176}Lu is one of the few naturally occurring radio nuclides that have survived from the era of nucleosynthesis. Its present isotopic abundance [1] is 2.6% and its half-life is 4.08×10^{10} yr [2].

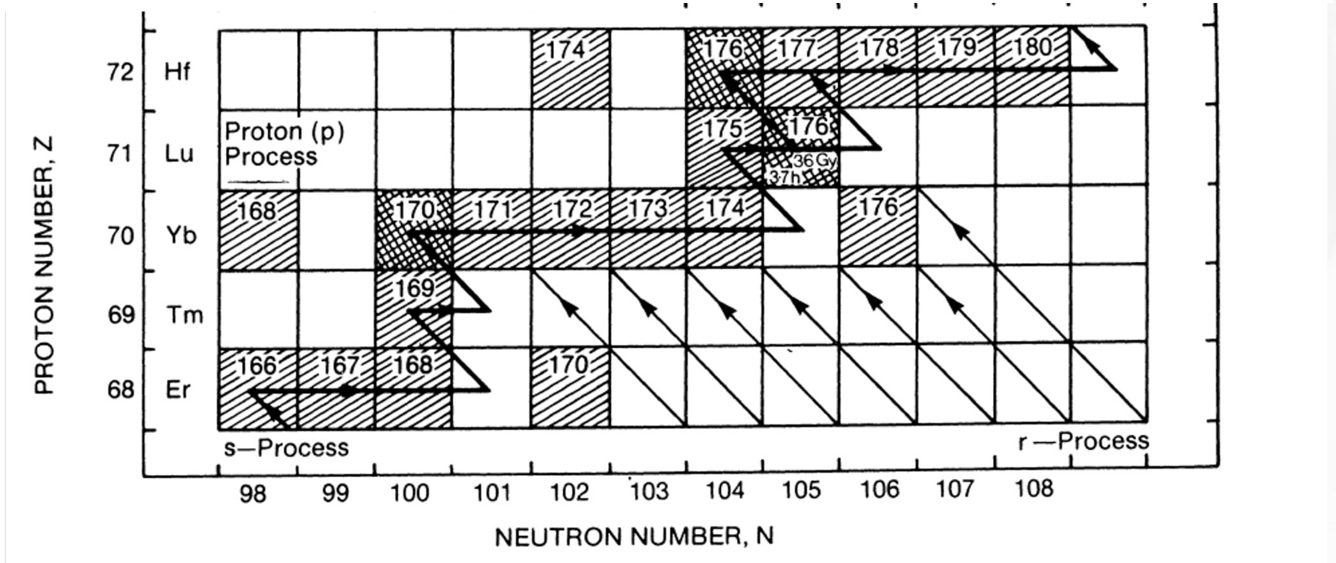
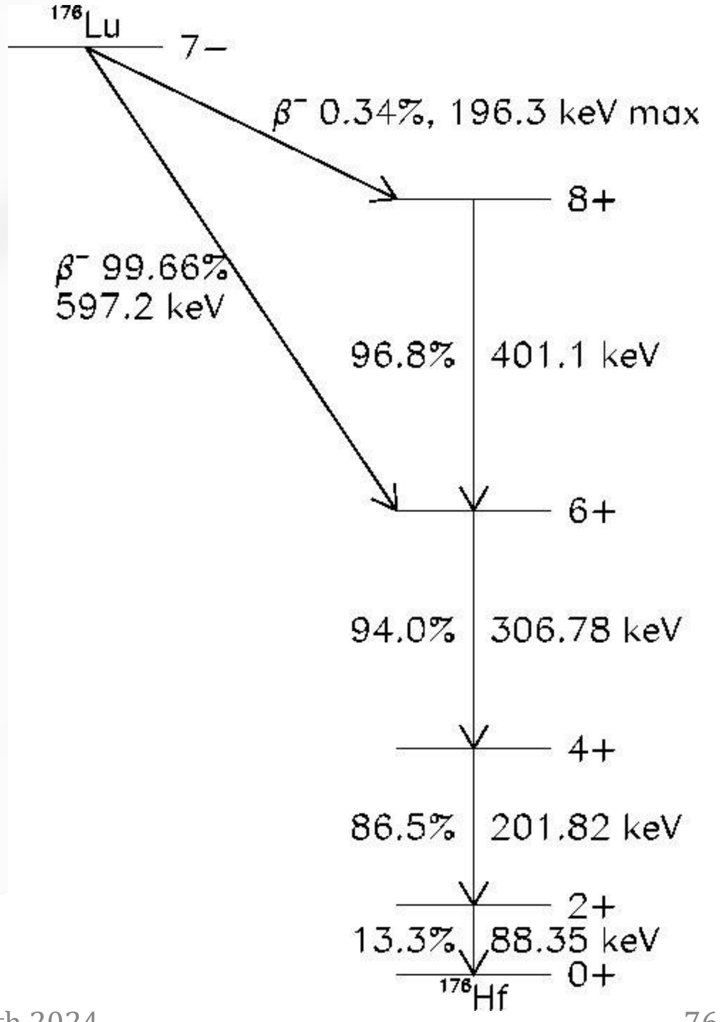


Figure 1. *s*-process path in the rare earth element mass region. *s*-only process nuclides ^{170}Yb, ^{176}Lu and ^{176}Hf are shielded from *r*-process contributions by ^{170}Er and ^{176}Yb respectively. The *s*-process branches at ^{176}Lu if a significant population of the 3.68 h isomeric state occurs.



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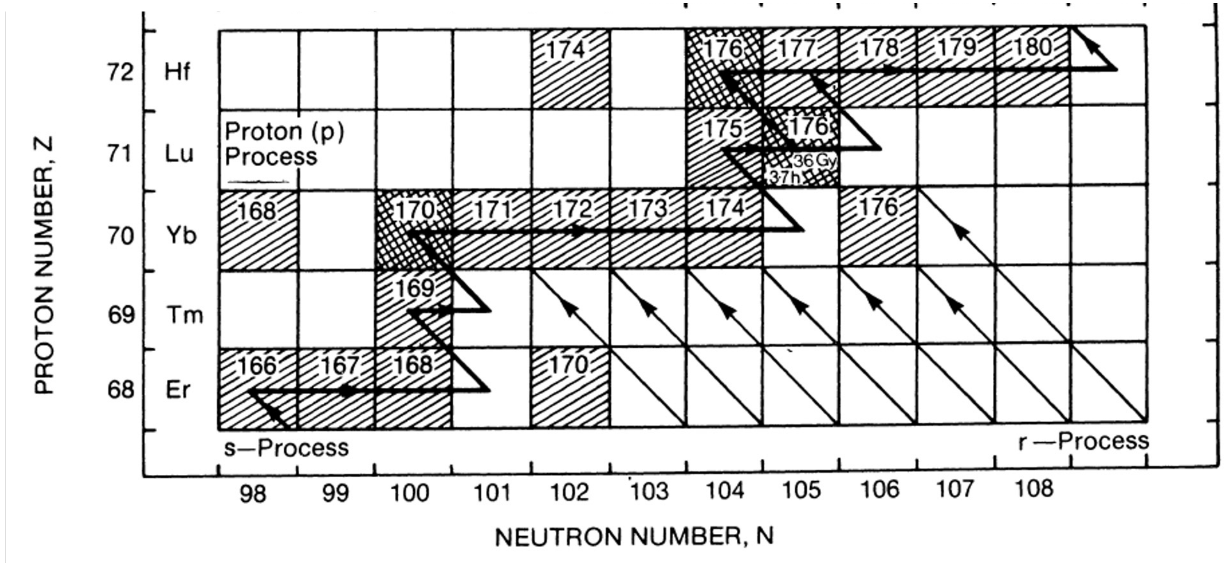
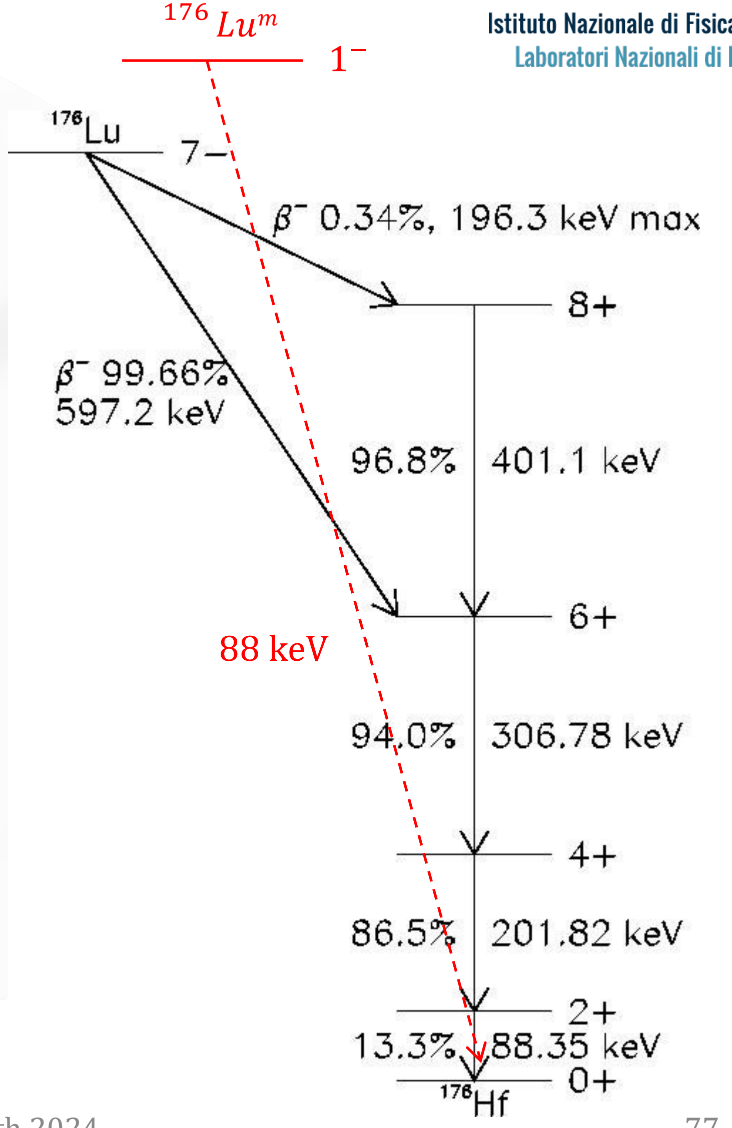


Figure 1. s-process path in the rare earth element mass region. s-only process nuclides ^{170}Yb, ^{176}Lu and ^{176}Hf are shielded from r-process contributions by ^{170}Er and ^{176}Yb respectively. The s-process branches at ^{176}Lu if a significant population of the 3.68 h isomeric state occurs.



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PHYSICAL REVIEW C VOLUME 44, NUMBER 6 DECEMBER 1991

^{176}Lu: An unreliable *s*-process chronometer

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and Center for Particle Astrophysics, University of California, Berkeley, California 94720

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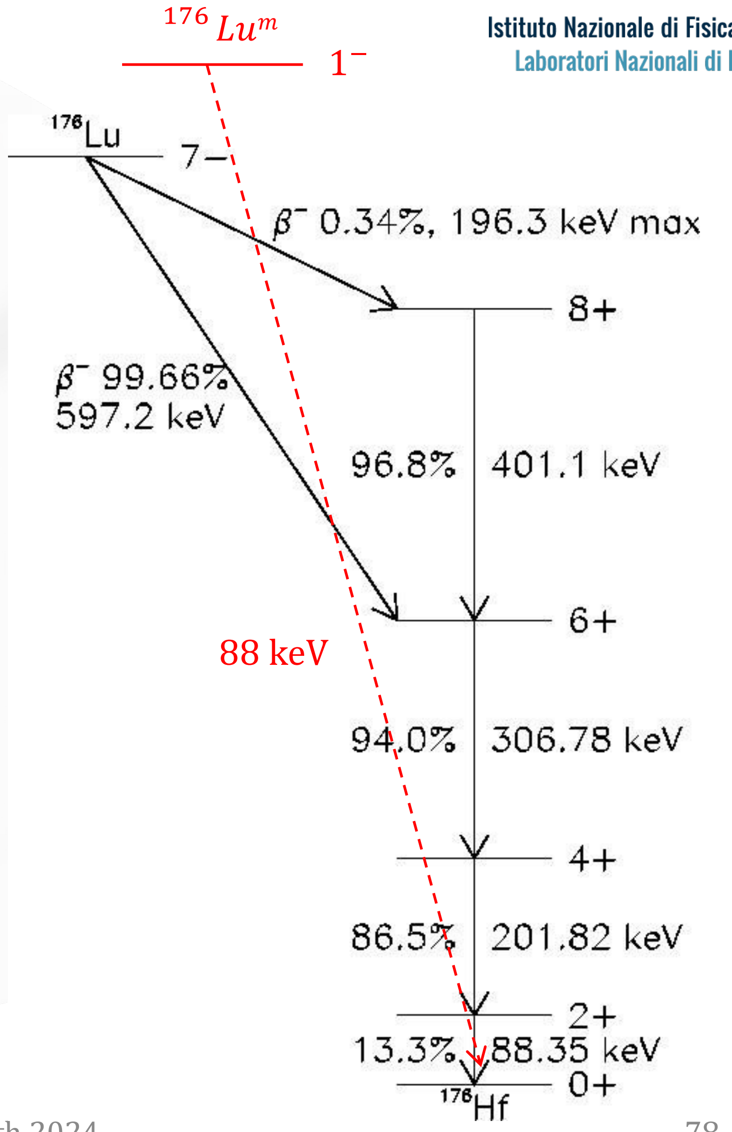
Nuclear Science Division, Lawrence Berkeley Laboratory, 1 Cyclotron Road, Berkeley, California 94720
(Received 17 October 1990)

A level scheme of ^{176}Lu up to ~1400 keV excitation energy is deduced from a γ-γ coincidence experiment and previously published particle transfer data. 170 γ-ray transitions are placed between 85 levels. We identify 27 previously unknown levels and 131 previously unknown transitions in ^{176}Lu. With this γ-ray data we place the energy of the isomer at 122.9 keV. A level at 838.5 keV ($J^{\pi}=5^{-}$, $t_{1/2}<10$ ns) is found to decay with substantial strength to both the ground state (7^{-}, 4.08×10^{10} yr) and the 122.9 keV isomer (1^{-}, 3.7 hr). The presence of this level guarantees the thermal equilibrium of ^{176}Lu^{g,m} for $T\geq3\times10^{8}$ K and therefore during *s*-process nucleosynthesis. The resulting temperature sensitivity of its effective half-life rules out the use of ^{176}Lu as an *s*-process chronometer. The use of ^{176}Lu to determine *s*-process temperatures is discussed.



Measurement strategy

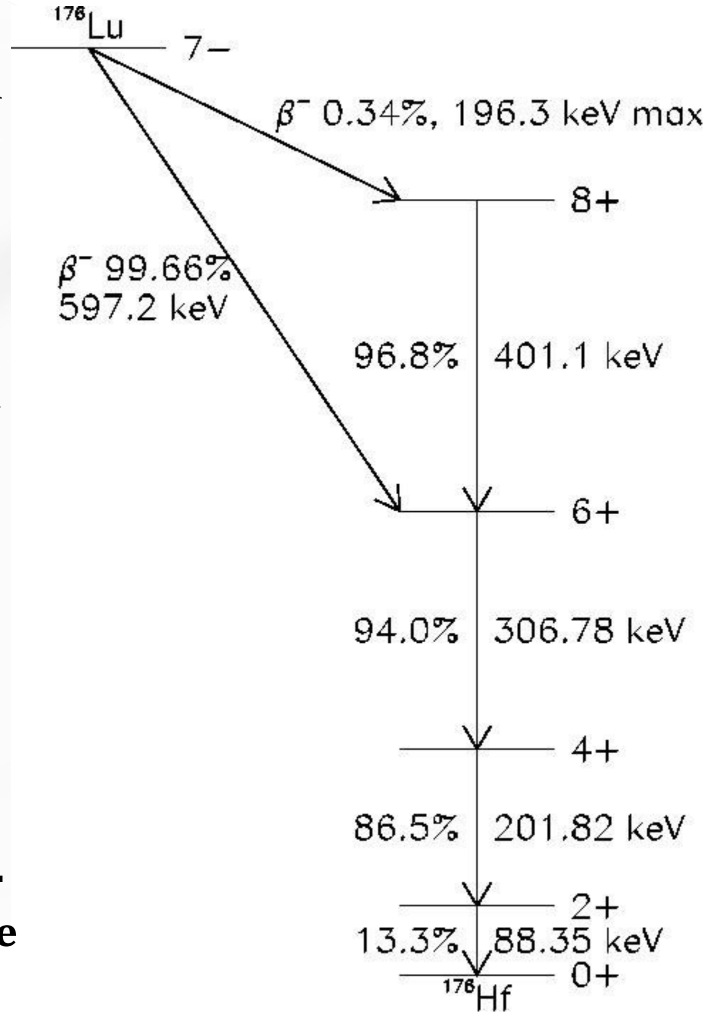
1. Once the solid ^{176}Lu target is hit by a laser pulse with an intensity as high as $10^{21}\ W/cm^2$, the ionization and the subsequent ion emission takes place

2. Lu ions travelling at a velocity of the order of hundreds of keV

3. Given the high energy administered by the laser in a short time interval, a local thermal equilibrium can be reached not only by the electrons, but also by the ion clouds, that can reach temperature as high as 10^8K

4. At this temperature, the nuclei may be excited, and the Lu isomeric state $^{176,m}Lu$ can be populated

5. **^{176}Lu decays to the Hf 6^+excited states, whose de-excitation proceeds through three different steps, leading to the subsequent emission of photons with energies equal to E_γ= 307, 202 and 88 keV. $^{176,m}Lu$, on the other hand, directly decays to the first Hf excited state → only the emission of a photon with E_γ = 88 keV is observed**



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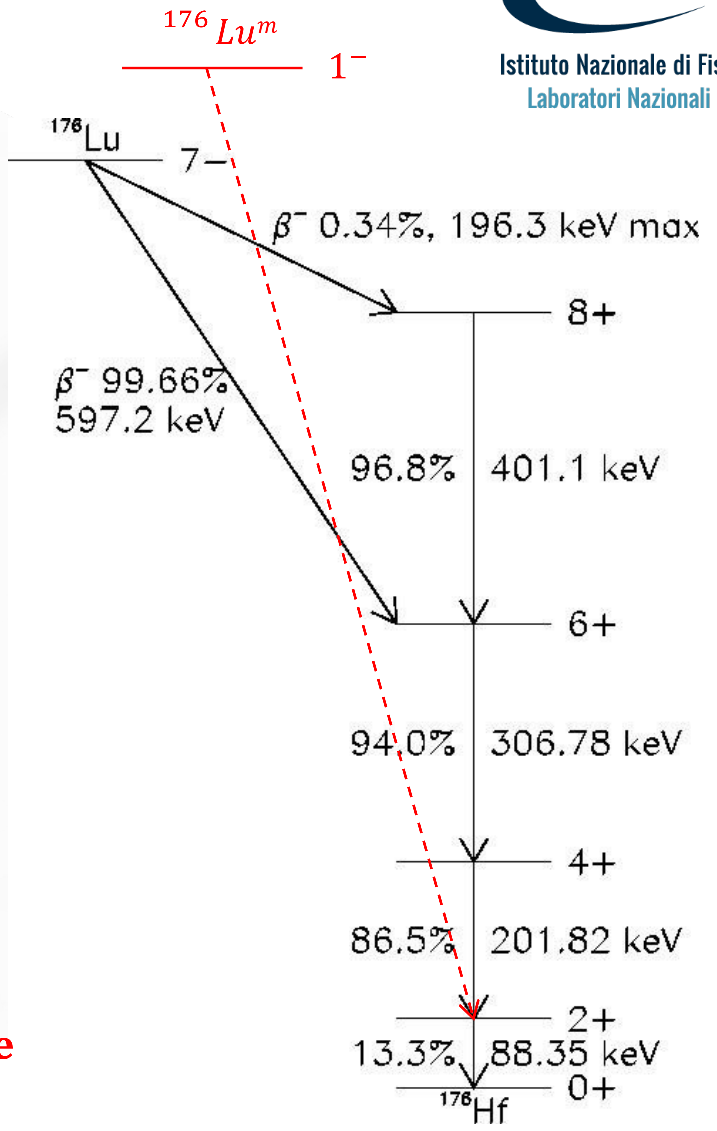

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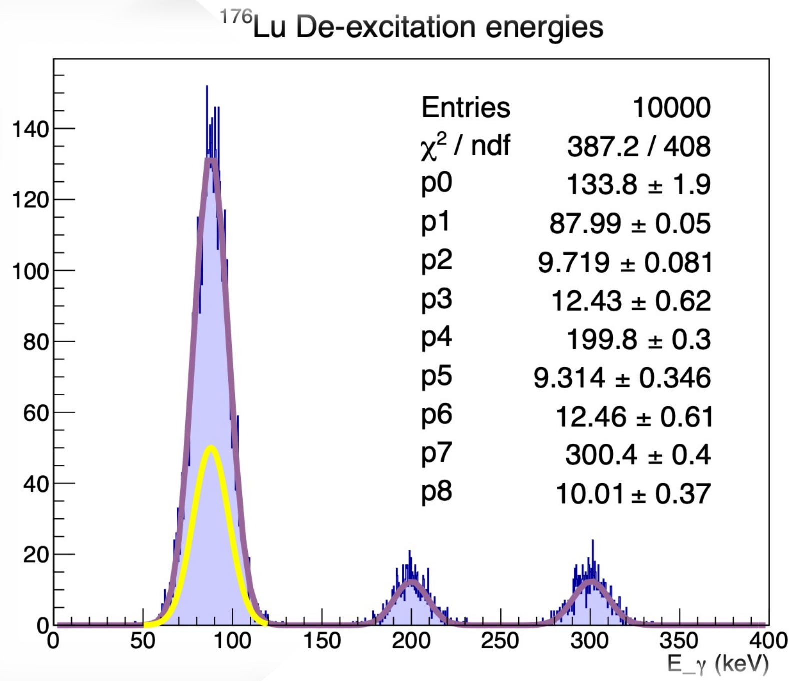
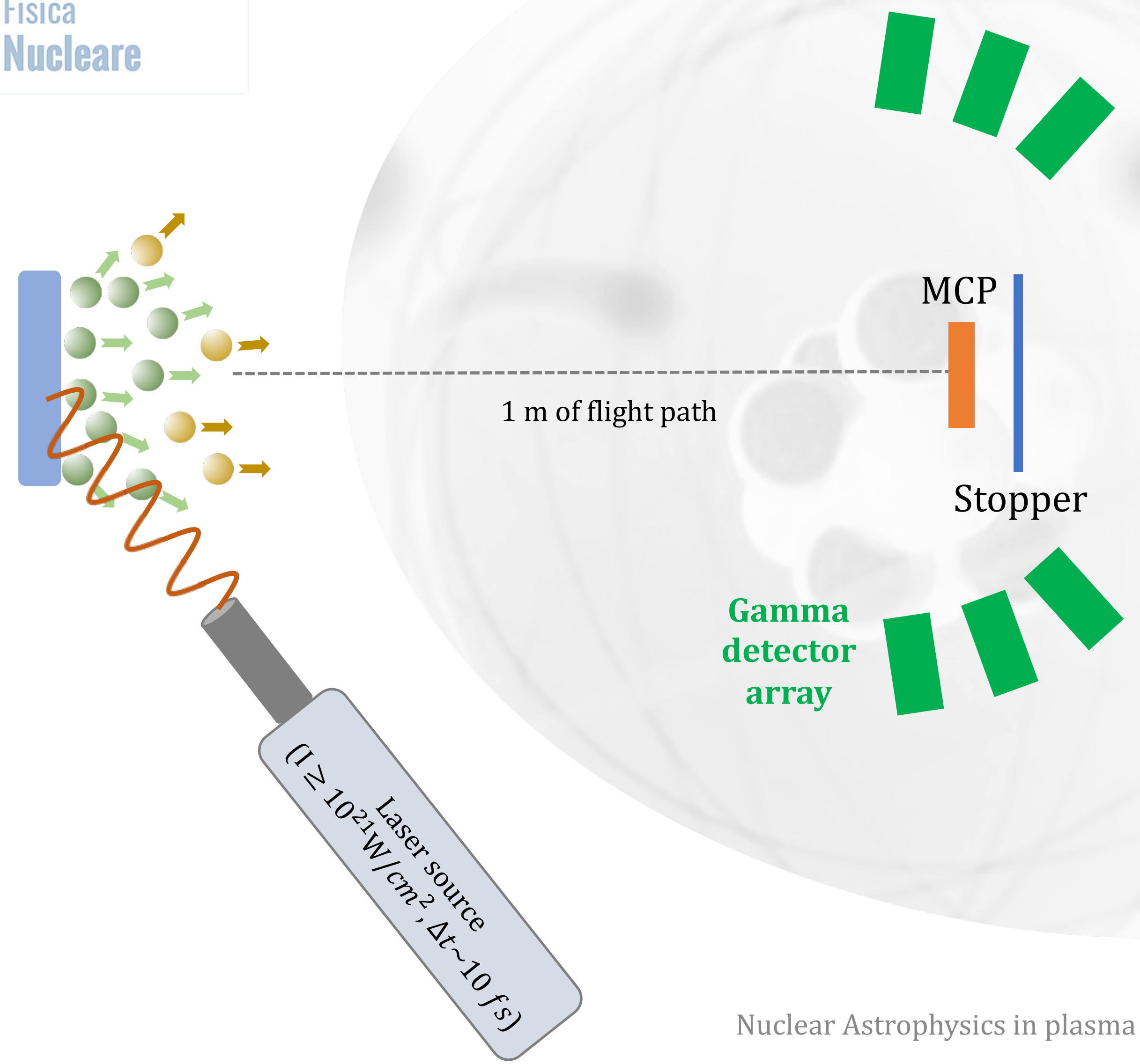
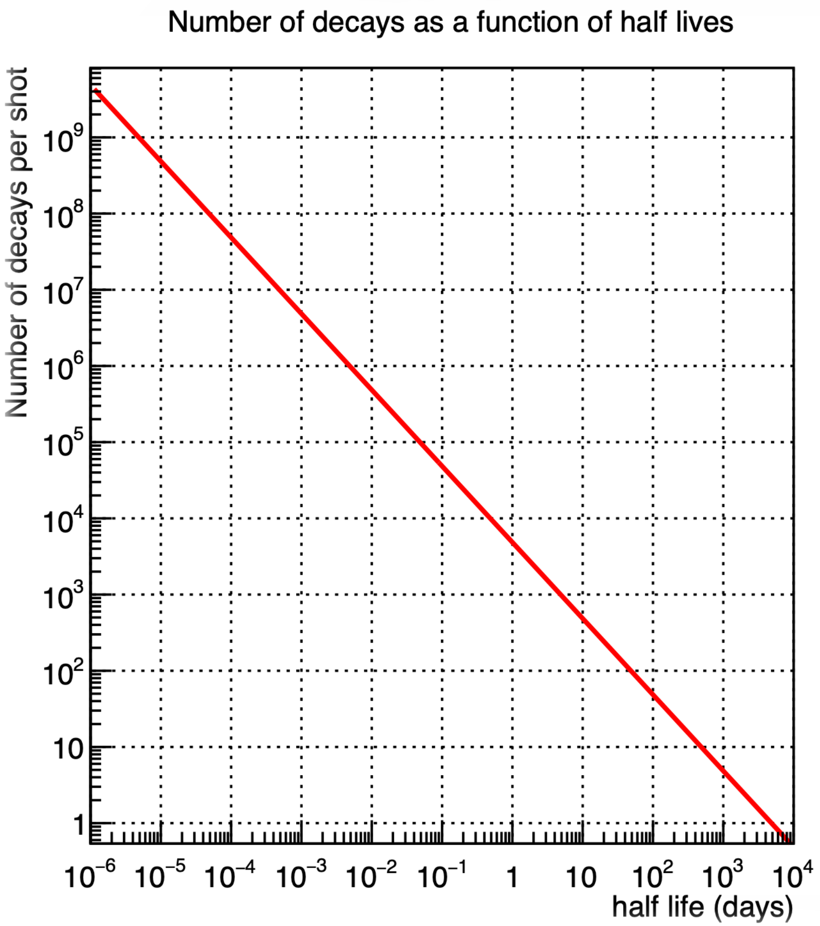


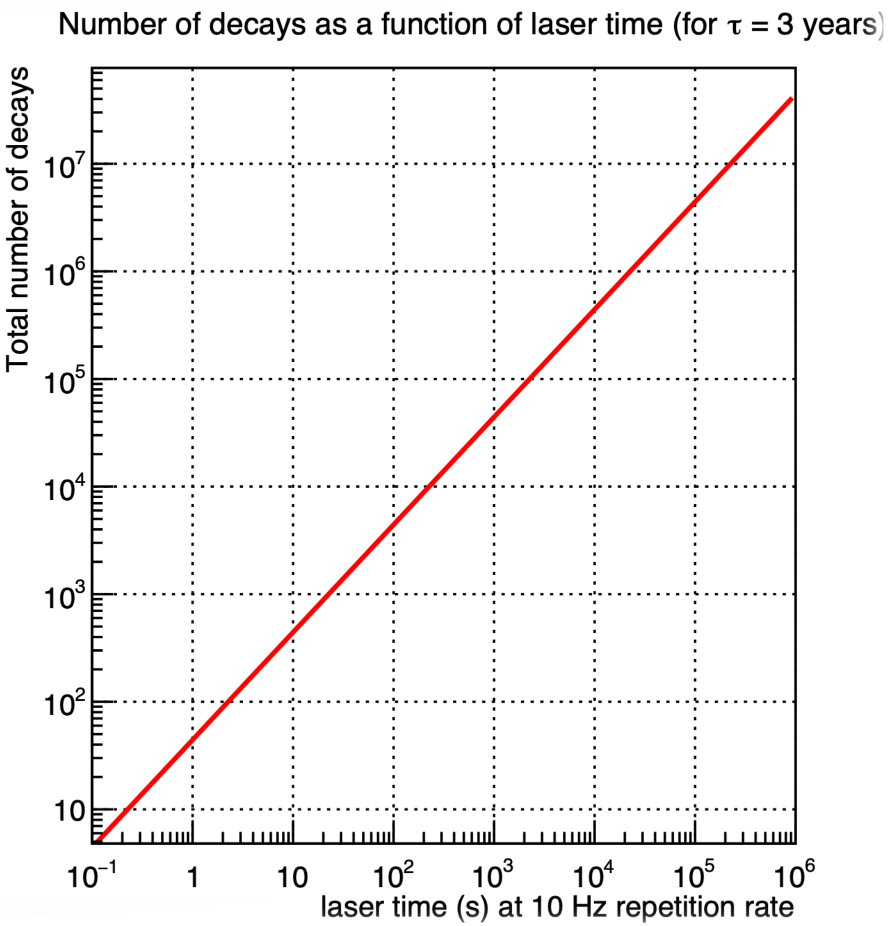
Possible experimental setup for β-decay



1. A PW laser pulse is sent to a solid target containing the radio-isotope under investigation.
2. The plasma is created and a forward emission of the thermalized excited nuclei takes place.
3. The nuclei travel and eventually decay in flight, populating daughter nuclei in excited states.
4. The flight path, and then the distance between the target and a suitable stopper, must be optimized in order to guarantee a proper time window for the decay measurement ($\sim 1\mu s$).
5. This poses limits on the half-life range that can be explored.
6. The gamma emitted in the decay process may be detected through a dedicated detection system.

Projections for a 10 Hz repetition rate





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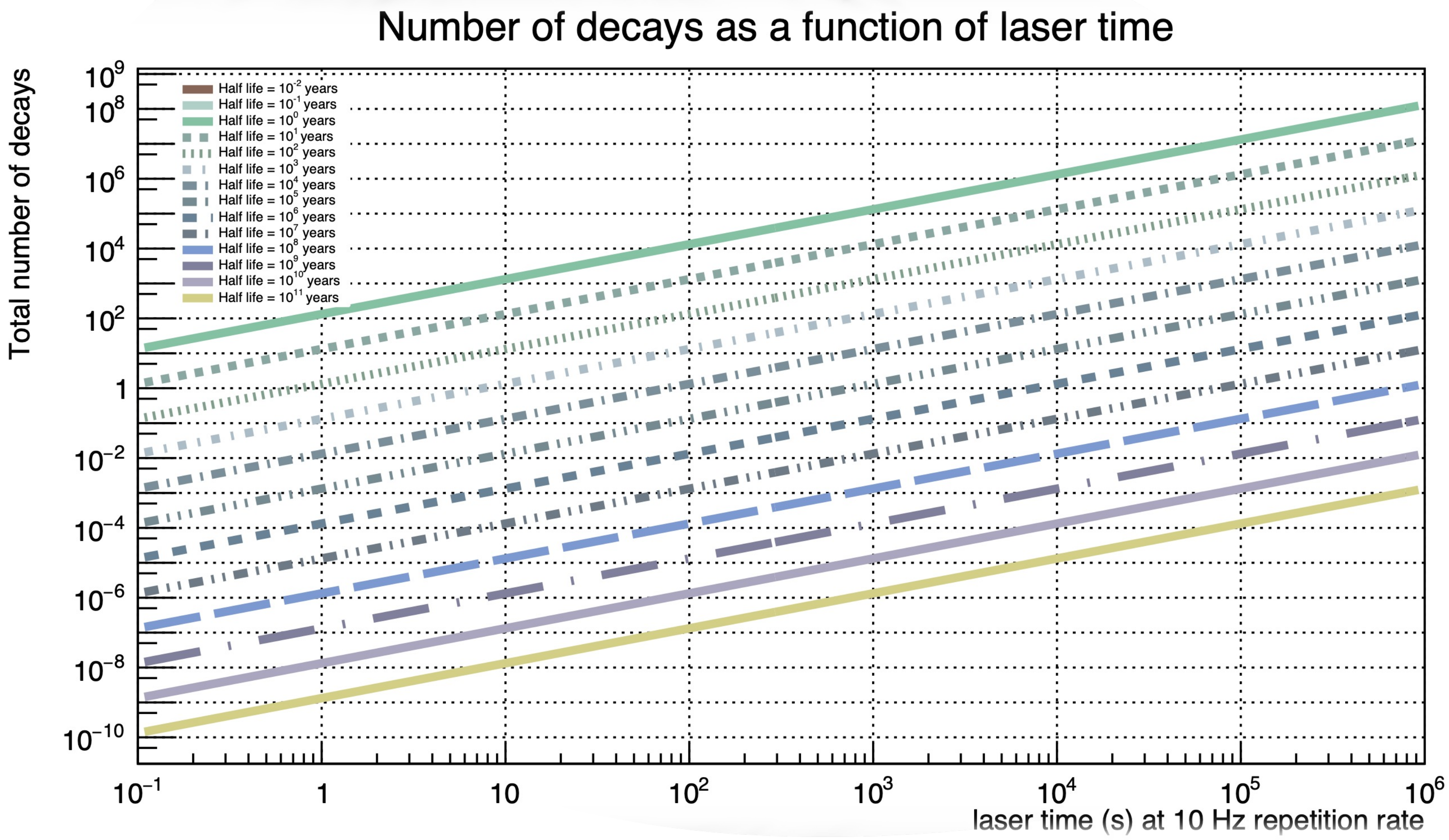
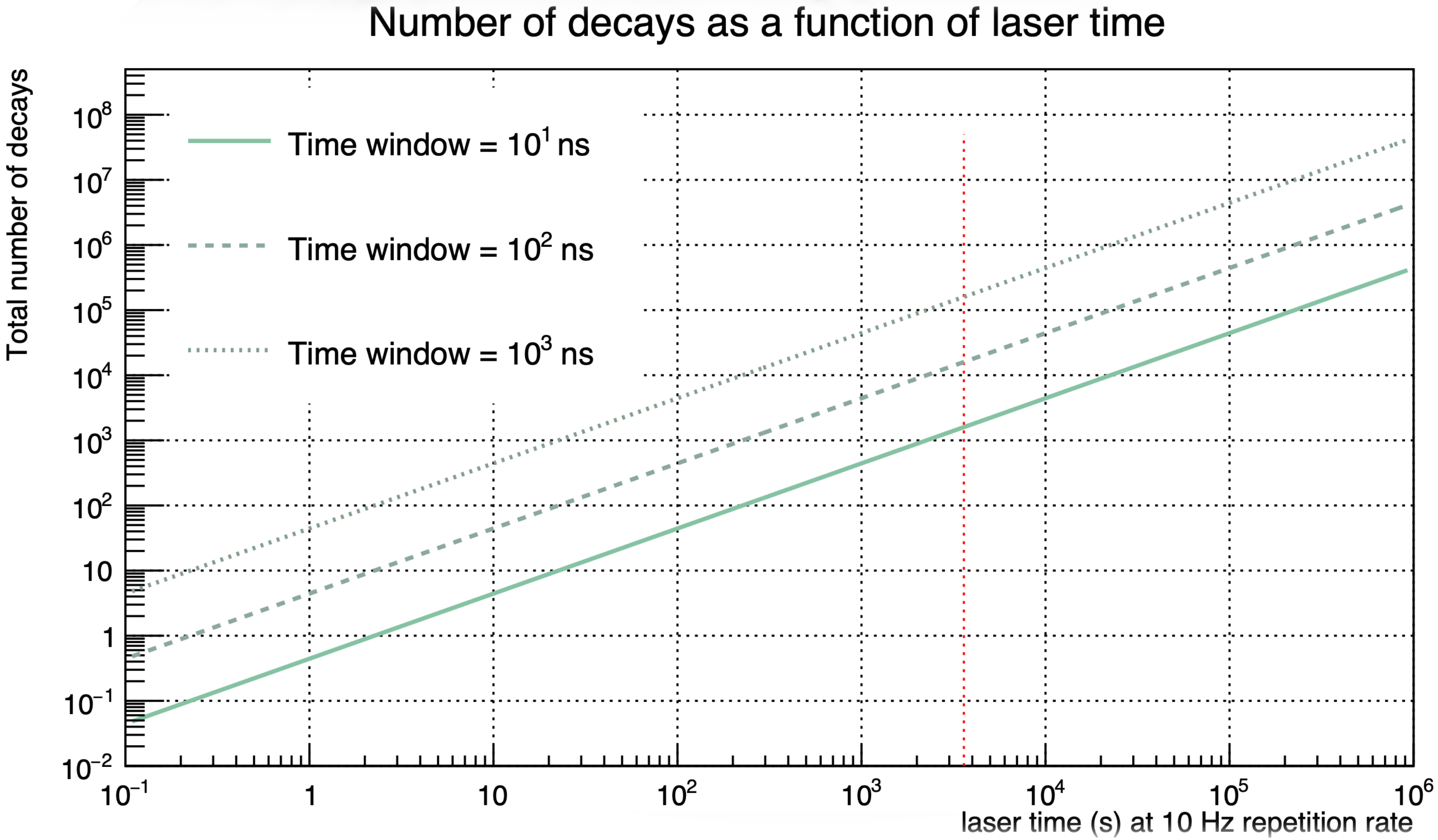
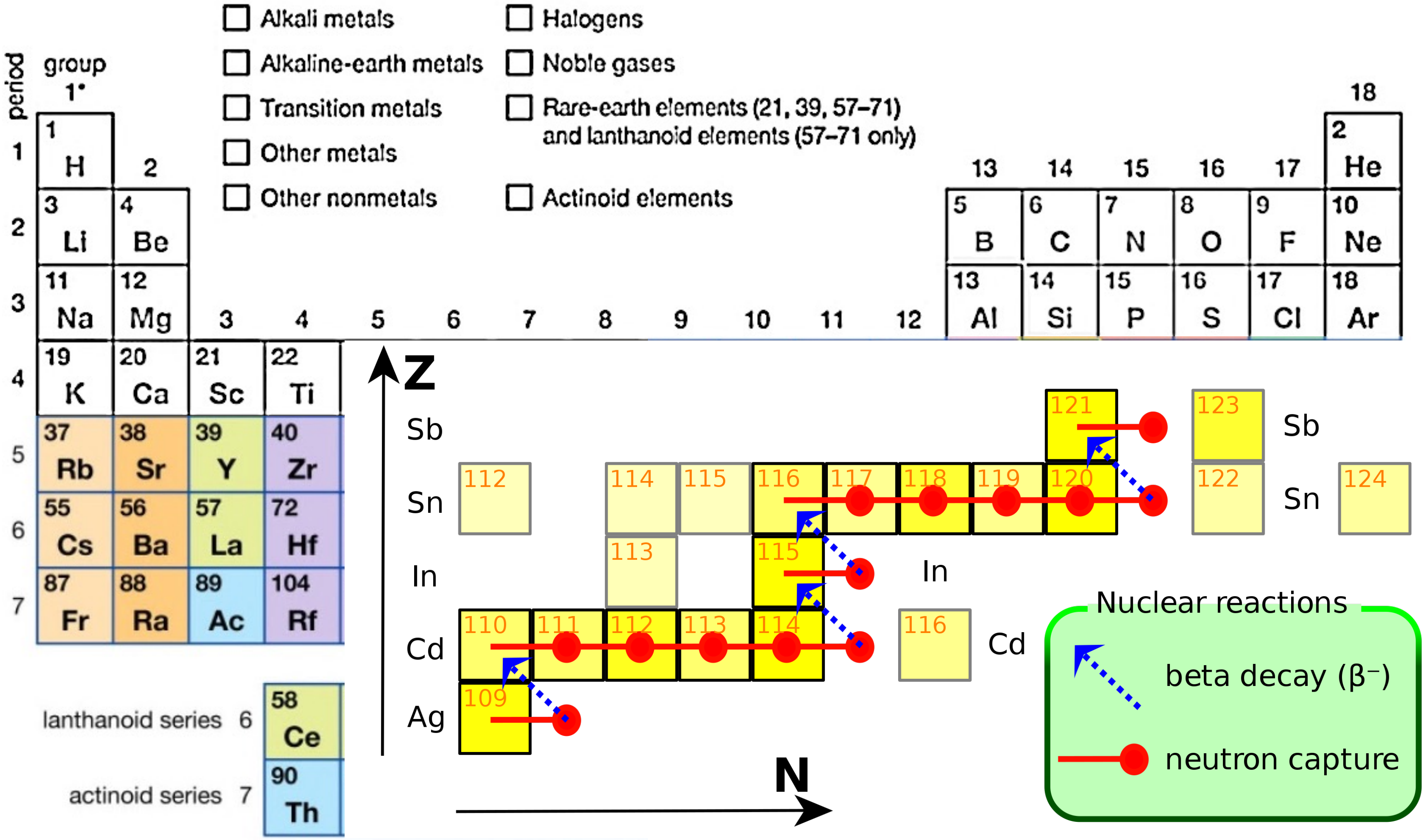


Projections for a 10 Hz repetition rate



Nuclear physics: general information

S- and *r*-process Nucleosynthesis



Solar system abundances

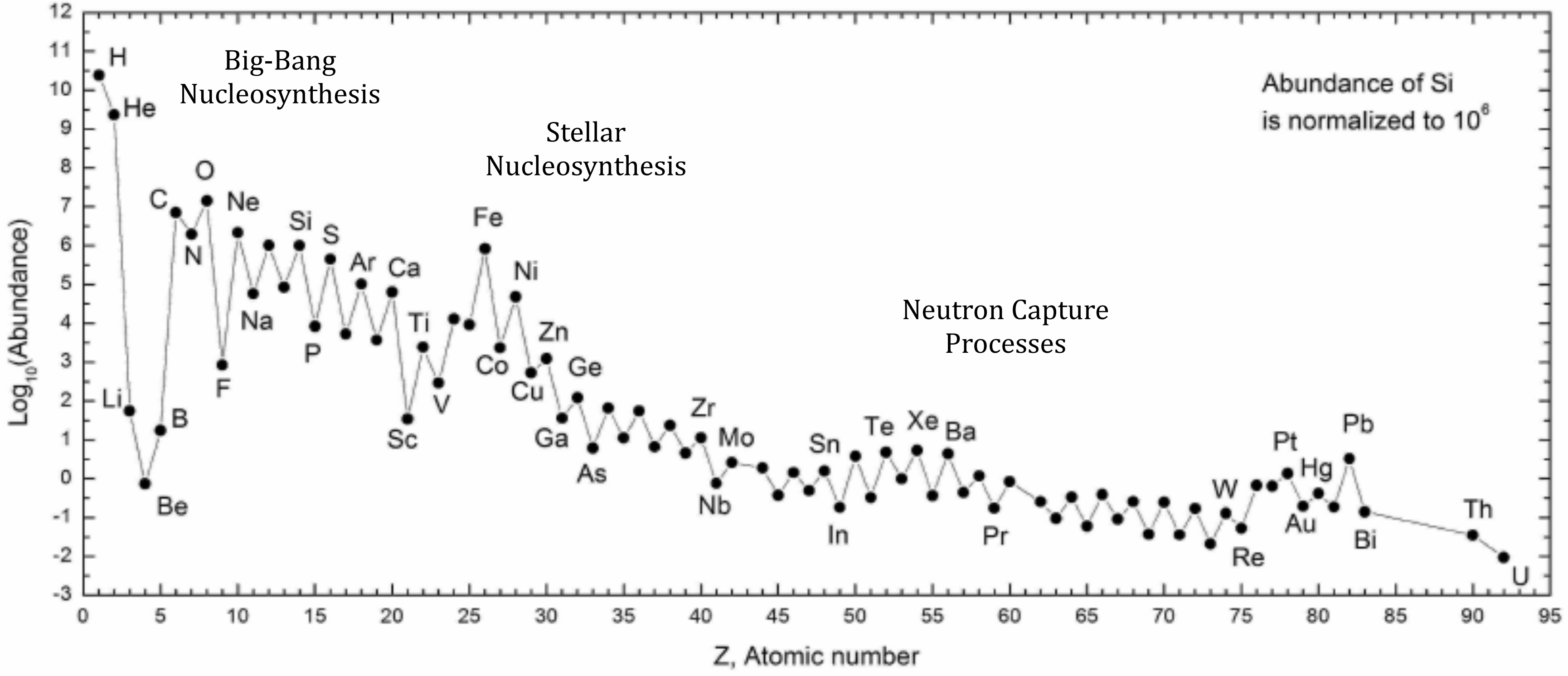
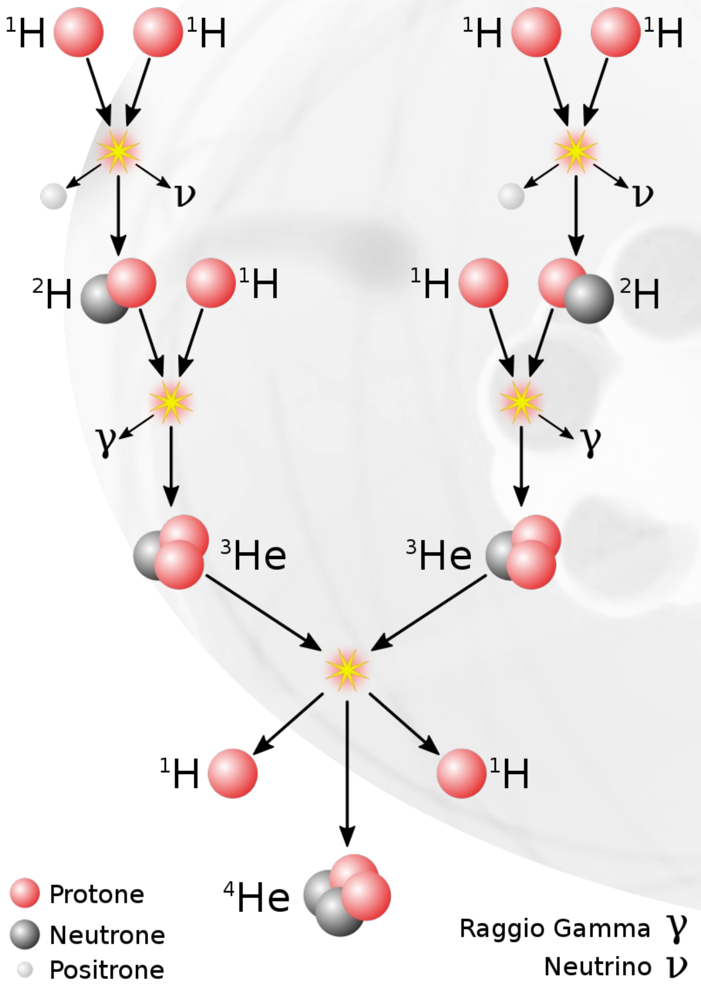
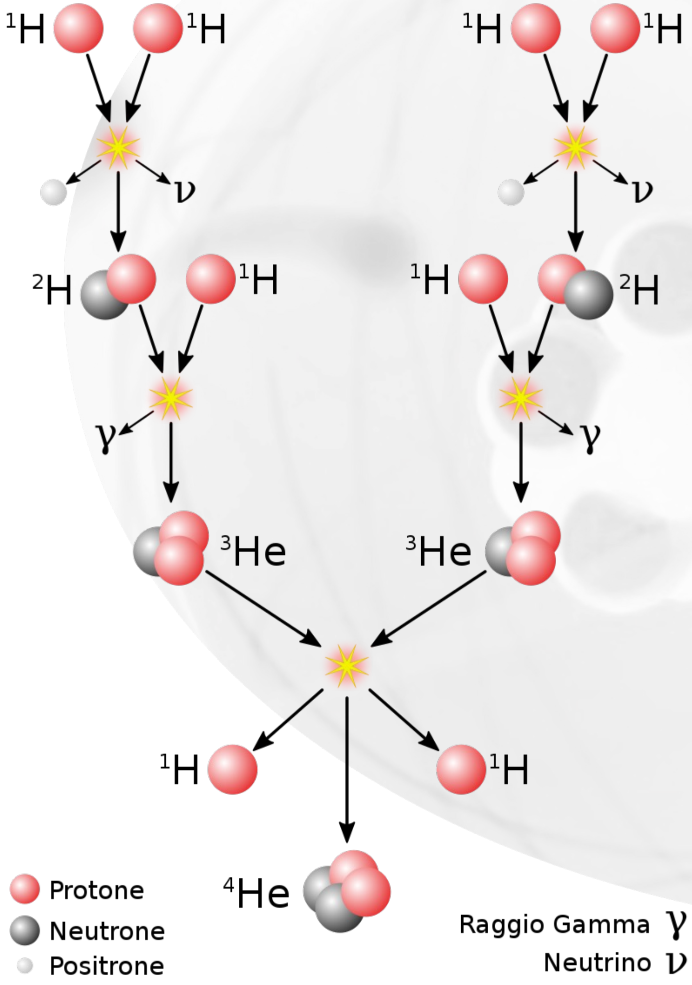


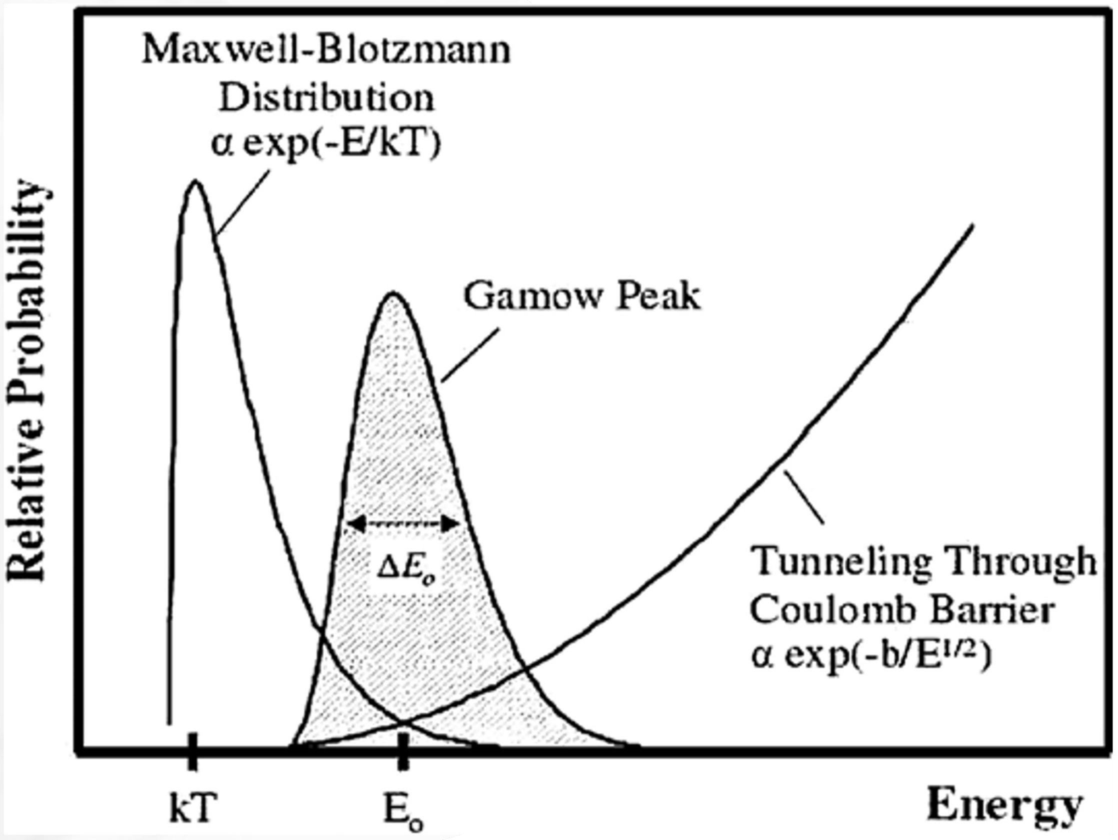
Figure 1.1: Solar abundance distribution normalised to Silicon at 10^6, adapted from Lodders 2003. The peaks in the distribution show the signatures of the different processes. The first peak around helium results from the primordial nucleosynthesis. The second peak around iron originates from nuclear statistical equilibrium and the following double peak structures from neutron capture processes.

Fusion processes: light elements

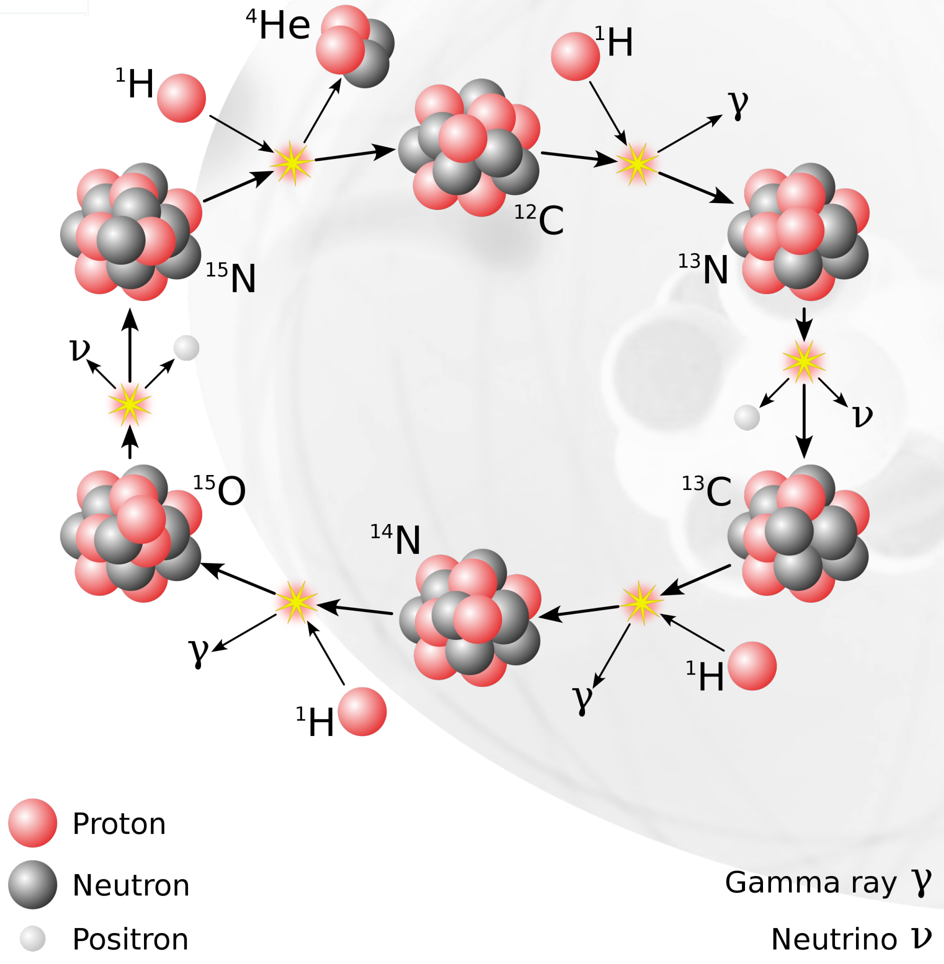


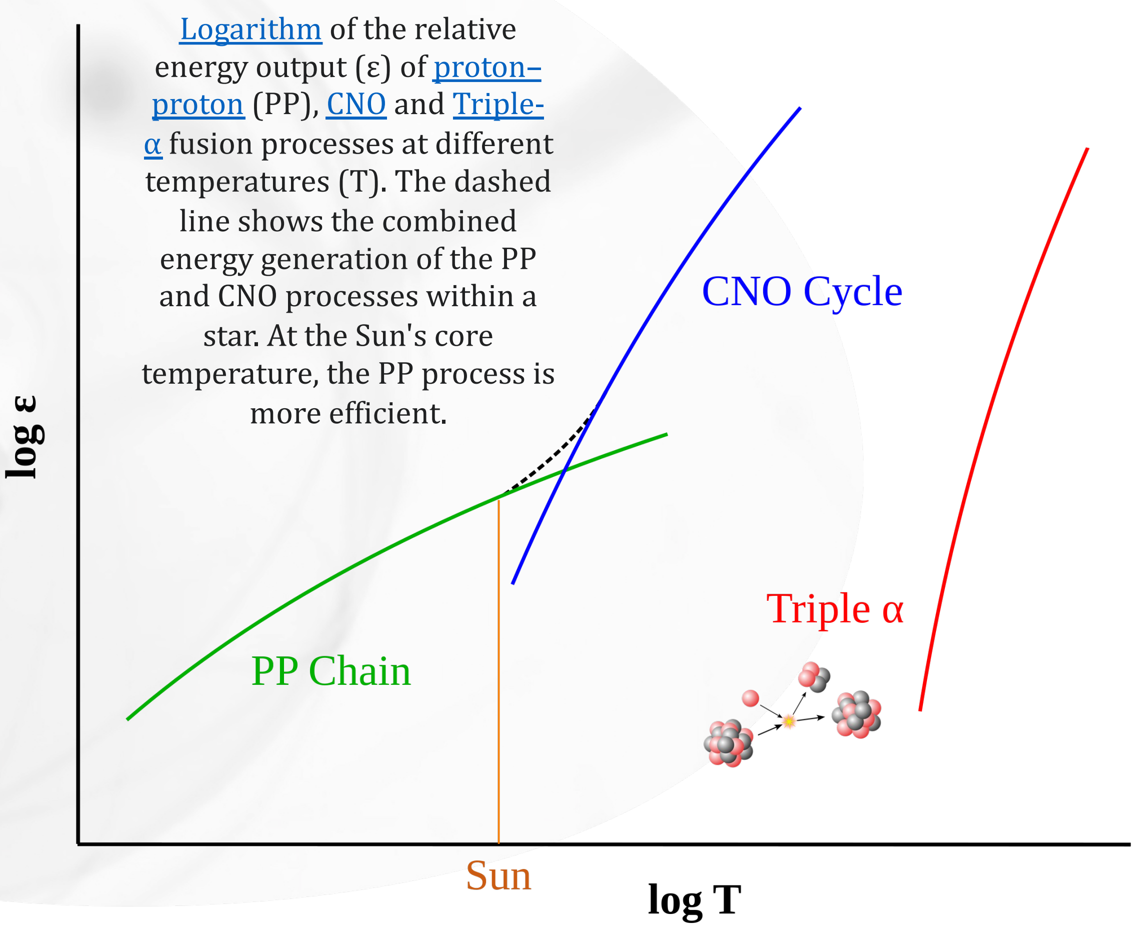
Fusion processes: light elements



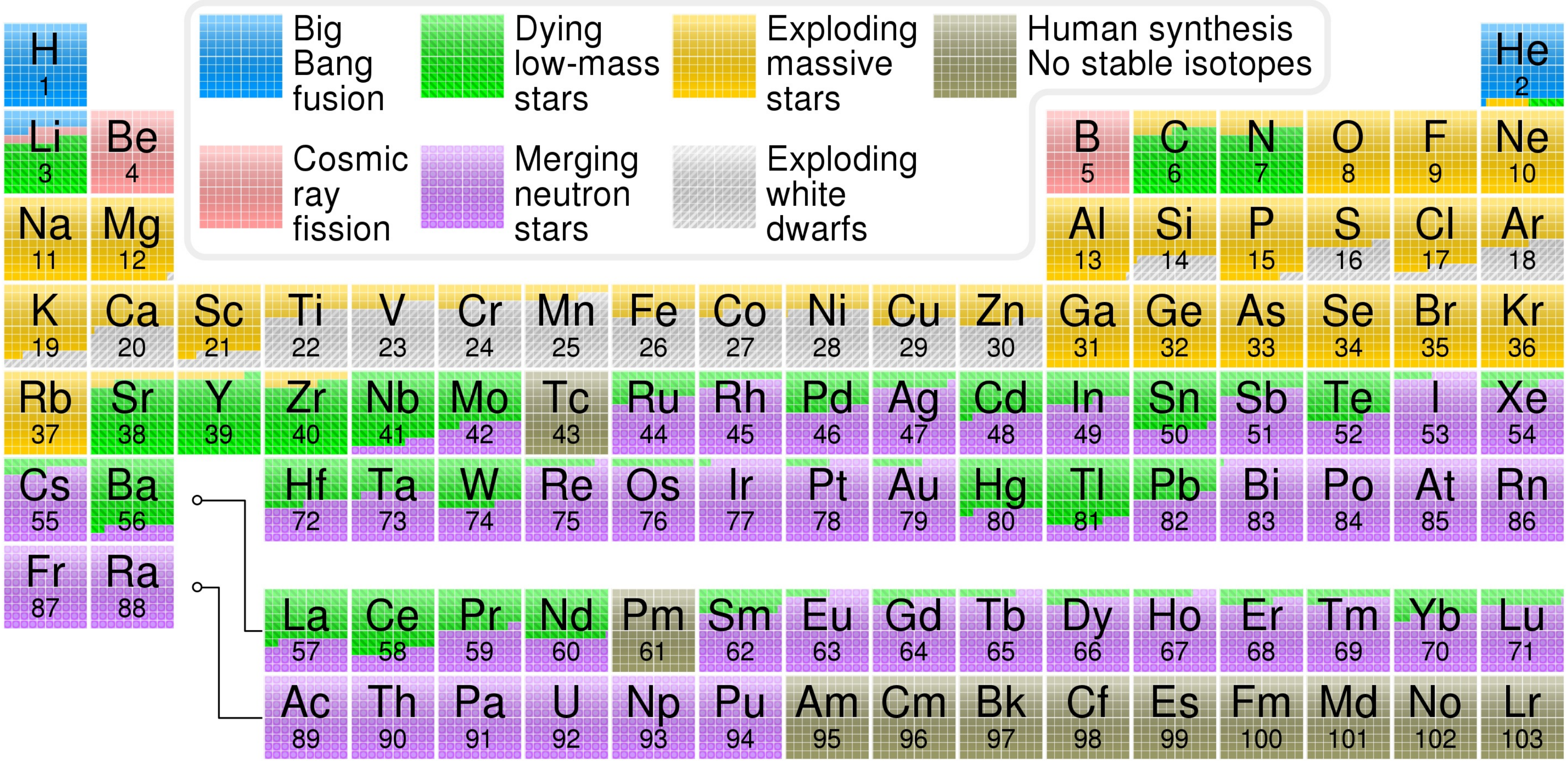


Fusion processes: elements up to Fe





Cosmogenic origin of elements



Main nucleosynthesis path

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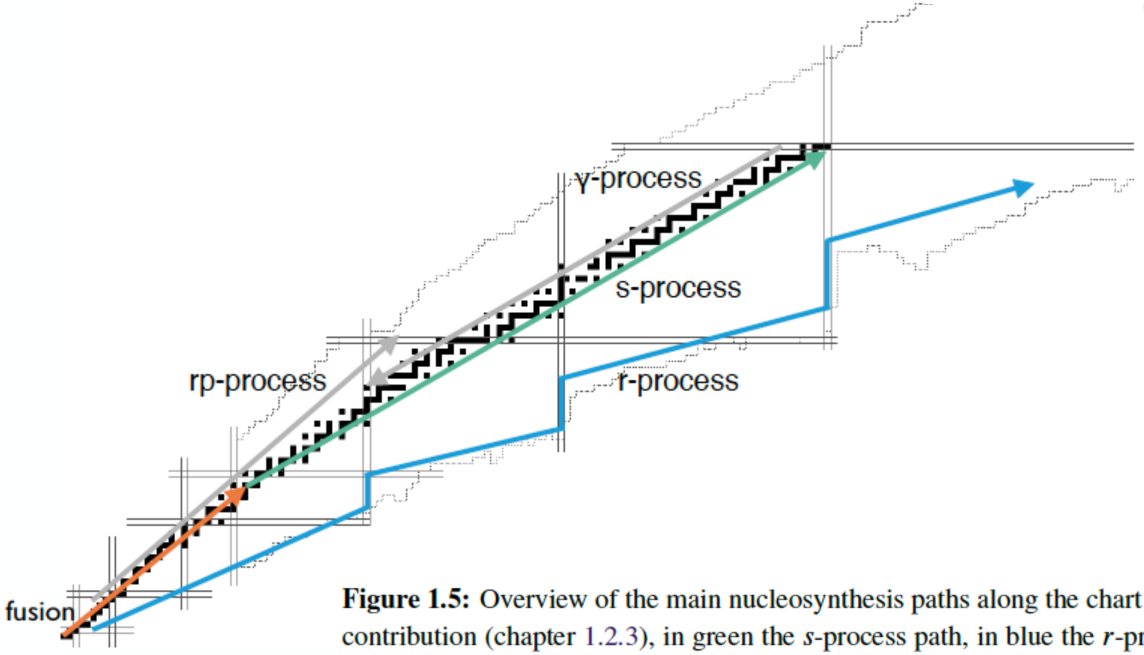
Figure 1.6: The *s*-process path. If a beta unstable isotope is reached, it decays back to the next stable isotope. Stable isotopes are marked grey, and unstable isotopes white.



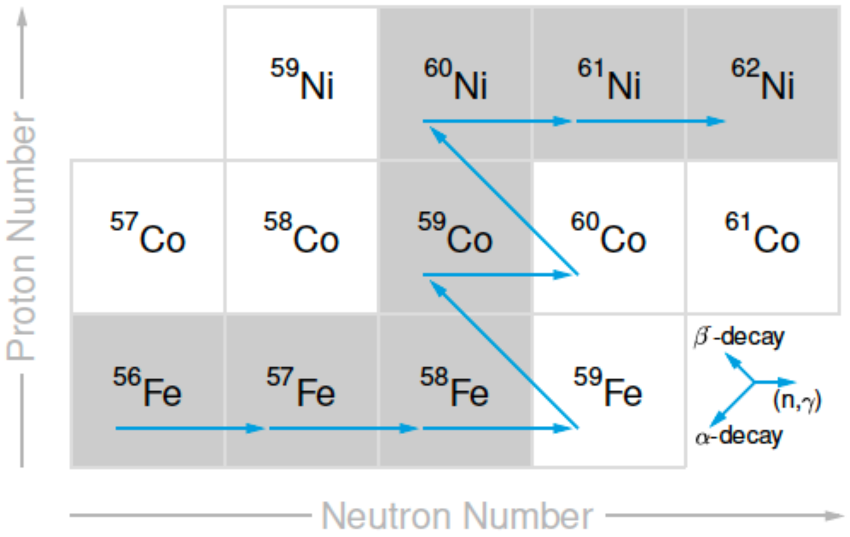


Figure 1.5: Overview of the main nucleosynthesis paths along the chart of nuclides. In orange the fusion contribution (chapter 1.2.3), in green the *s*-process path, in blue the *r*-process path (page 24) and in grey the *rp*- and γ processes (page 24). The *s* process and the γ process are secondary processes, which depend on certain seed isotopes, whereas fusion, the *r* process and the *rp* process are primary processes, which are not dependent on prior nucleosynthesis. Adapted from Glorius 2013.

Branching points and s-only isotopes

Branching points

Branching points are isotopes or isomers on the *s*-process path, which undergo a β-decay on the same timescale as a neutron capture. This leads to a branching in the *s*-process path where some of the mass flow follows the β-decay branch and the rest of the mass flow the neutron capture path (figure 1.10).

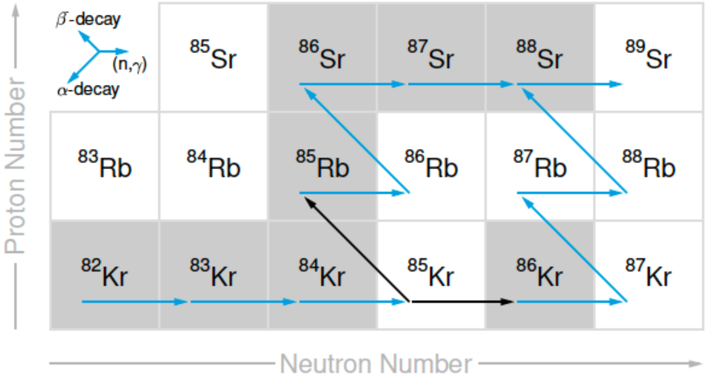
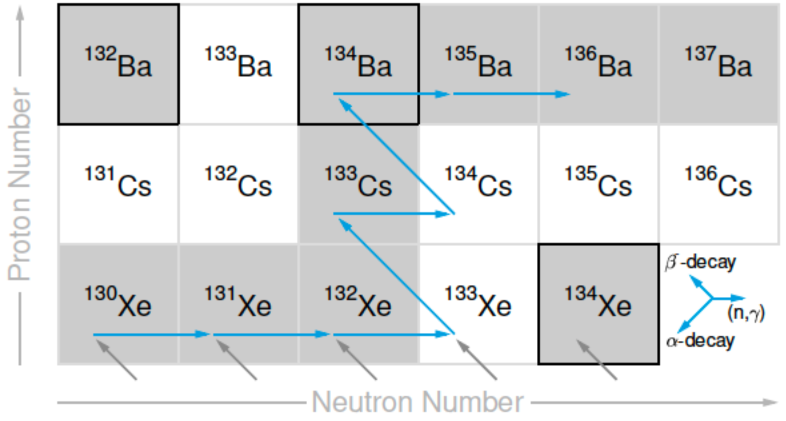


Figure 1.10: Branching point ^{85}Kr along the *s*-process path. ^{85}Kr has a half-life of about 10 years, which would make it an excellent probe for *s*-process conditions, if all reaction channels would be known to good precision. Stable isotopes are marked grey, and unstable isotopes white.

The *s*-only isotopes

The *s*-only isotopes are isotopes, which are created almost solely by the *s* process and are shielded from other processes. These isotopes are often considered when comparing observations to simulations (figure 1.11).



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^{176}Lu level scheme

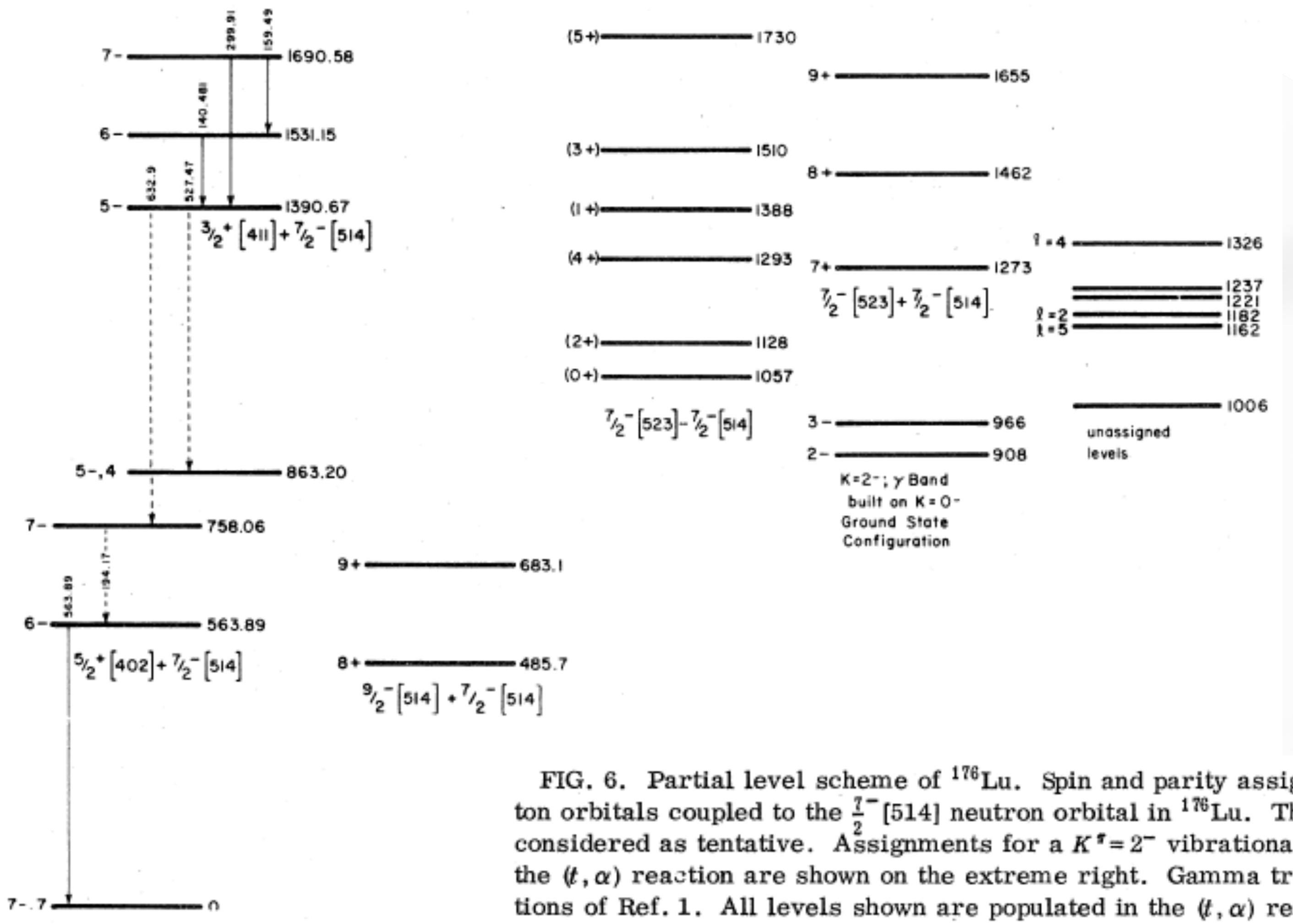

FIG. 6. Partial level scheme of ^{176}Lu. Spin and parity assignments of the $\frac{3}{2}^+$[411], $\frac{7}{2}^-$[523], $\frac{5}{2}^+$[402], and $\frac{9}{2}^-$[514] proton orbitals coupled to the $\frac{7}{2}^-$[514] neutron orbital in ^{176}Lu. The assignments for the $K^\pi = 0^+$ $\frac{7}{2}^-$[523] $-$ $\frac{7}{2}^-$[514] band are considered as tentative. Assignments for a $K^\pi = 2^-$ vibrational band are included and the unassigned levels populated in the (t, α) reaction are shown on the extreme right. Gamma transitions assigned were taken from unassigned transitions of Ref. 1. All levels shown are populated in the (t, α) reaction.

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^{176}Lu physics case

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

The Decay Scheme of Natural Lutetium 176

JAMES R. ARNOLD AND THOMAS SUGIHARA*
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received February 26, 1953)

THE nuclide lutetium 176 is of particular interest for two related reasons; first, that it is the central member of one of the four known triads of naturally occurring adjacent isobars, and second, that its spin of at least 7 units[1] is the highest known. Flammersfeld has reported a decay scheme for this nuclide,[2] in which both K capture and β-decay appear, the ratio of the branches being $K/\beta^- = 2$. The observed gamma-ray was placed in the K branch, and its energy fixed at 0.260 Mev.

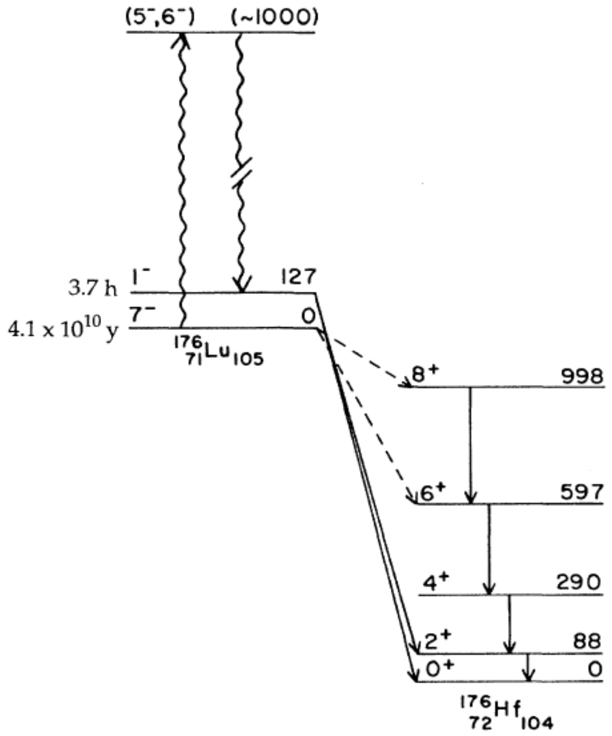
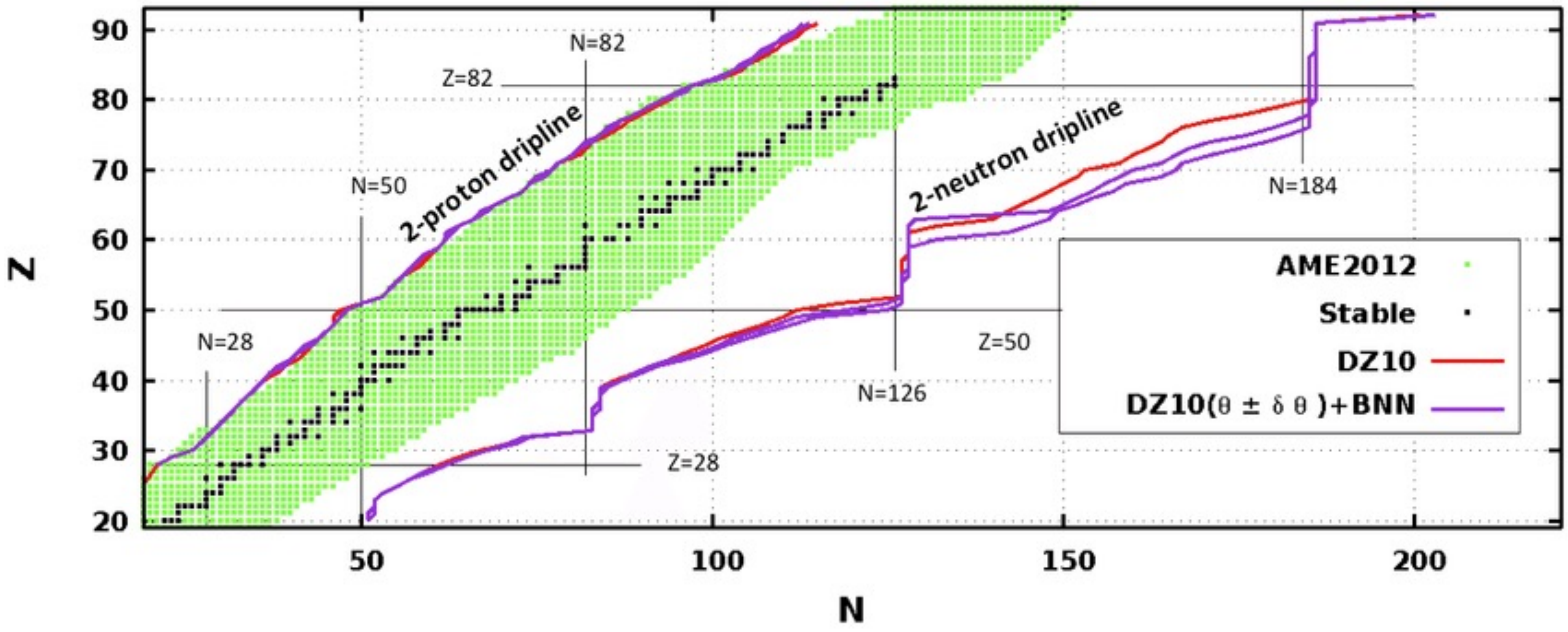


FIG. 3. A partial level scheme of ^{176}Lu, showing the positions and decays of the ground state and isomer at 122.9 keV. The equilibration of these two levels could be achieved by way of a level of intermediate spin, as illustrated in the figure.

Drip lines



Z
N
2-proton dripline
2-neutron dripline
N=28
N=50
N=82
N=126
N=184
Z=28
Z=50
Z=82
AME2012
Stable
DZ10
DZ10(θ ± δ θ)+BNN

^{176}Lu physics case

PHYSICAL REVIEW C VOLUME 44, NUMBER 6 DECEMBER 1991

^{176}Lu: An unreliable *s*-process chronometer

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^{176}Lu physics case

^{176}Lu is one of the few naturally occurring radio nuclides that have survived from the era of nucleosynthesis. Its present isotopic abundance [1] is 2.6% and its half-life is 4.08×10^{10} yr [2].

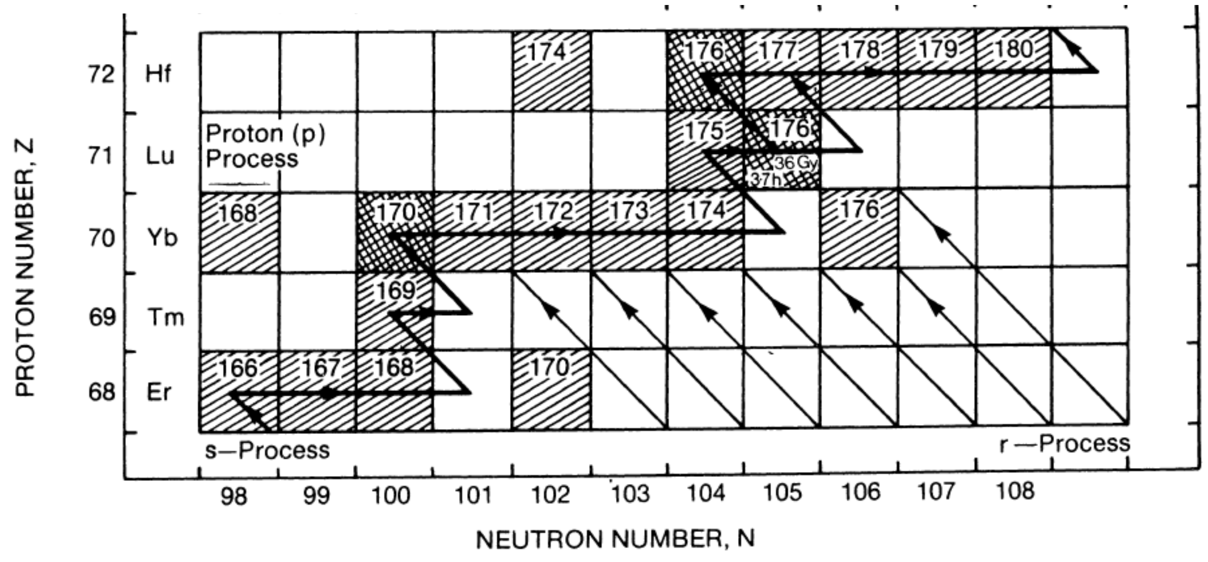
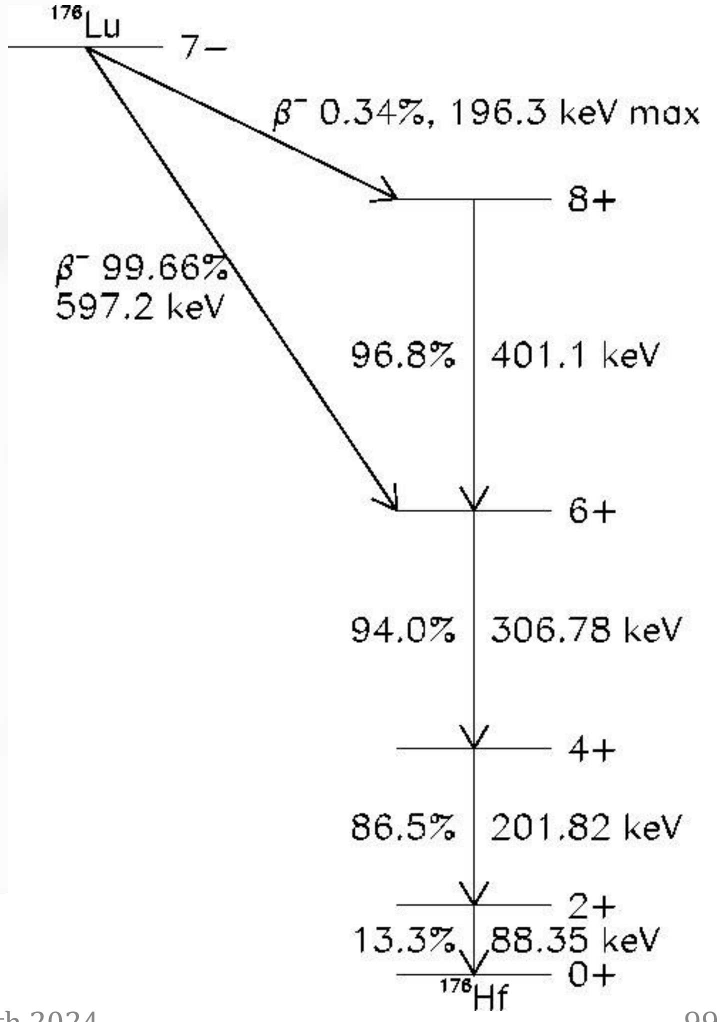
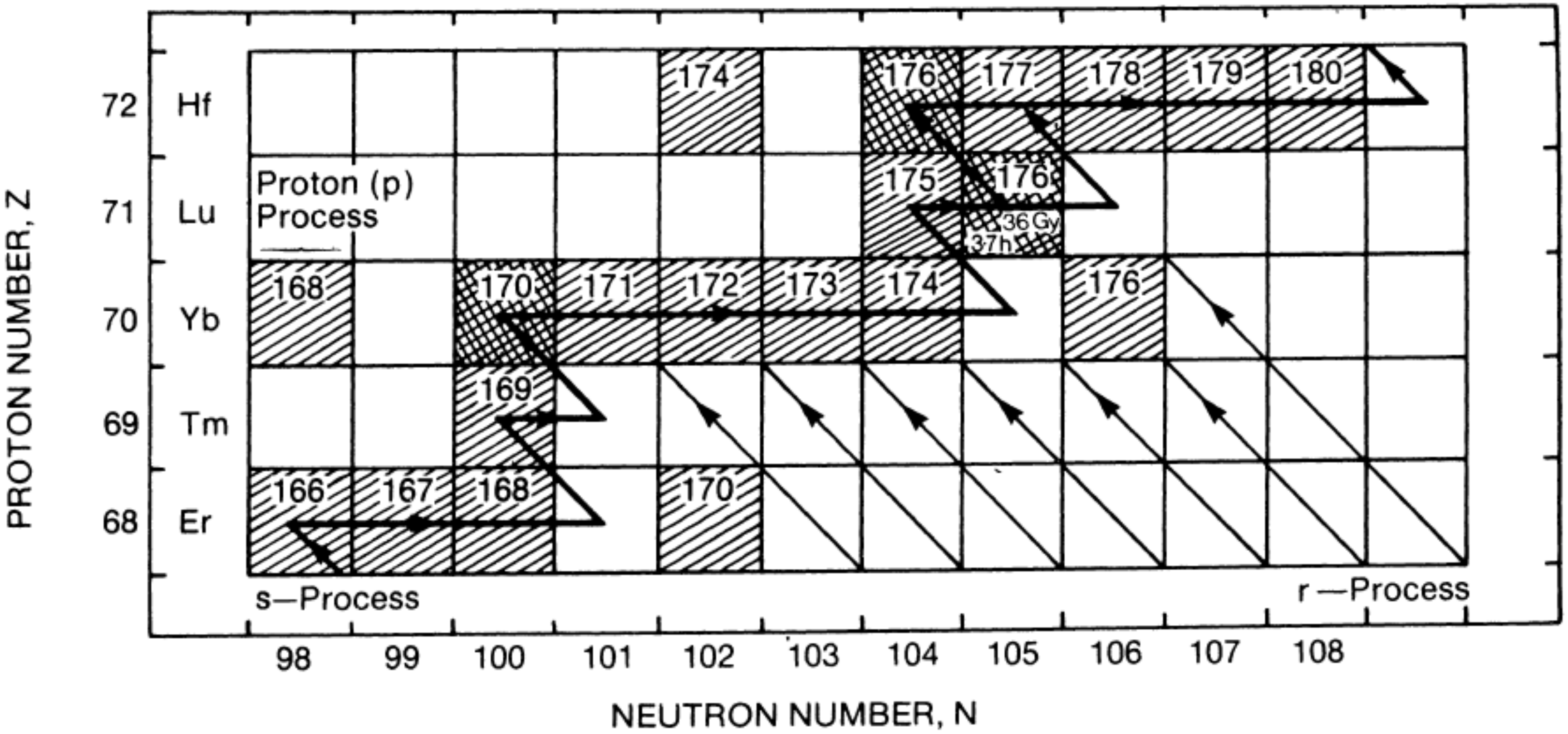


Figure 1. *s*-process path in the rare earth element mass region. *s*-only process nuclides ^{170}Yb, ^{176}Lu and ^{176}Hf are shielded from *r*-process contributions by ^{170}Er and ^{176}Yb respectively. The *s*-process branches at ^{176}Lu if a significant population of the 3.68 h isomeric state occurs.



^{176}Lu branch in the s-process



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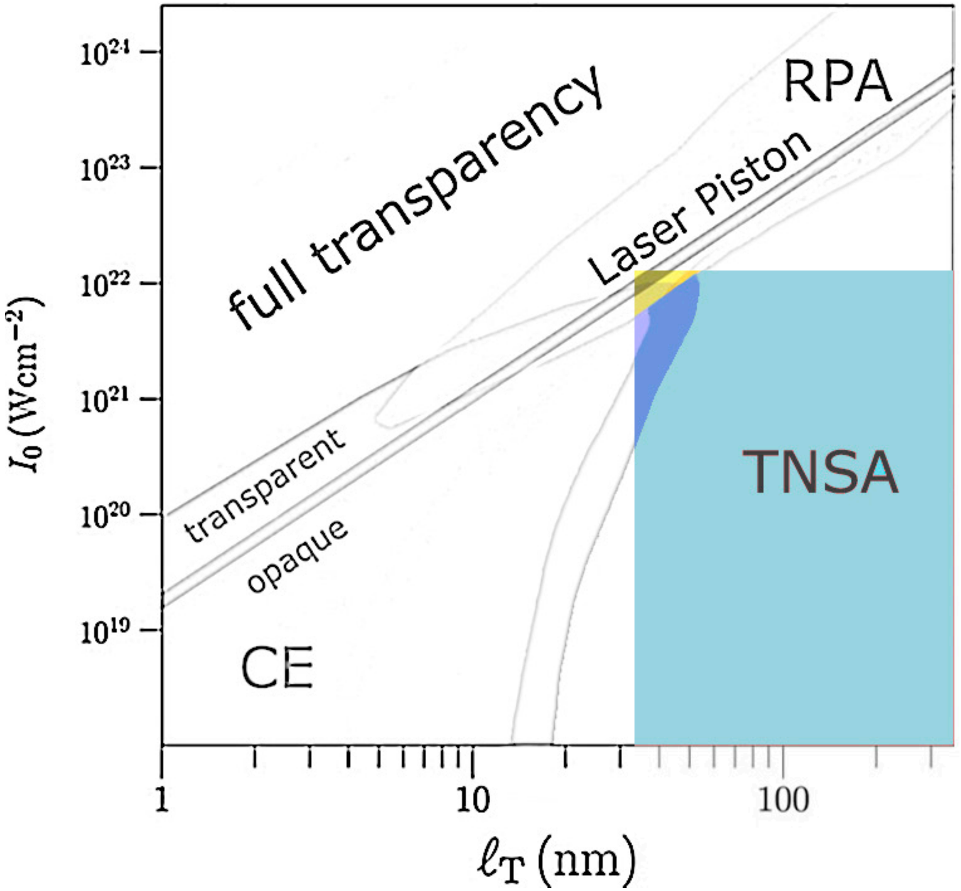
Experiments at the PW regime



High-density target → solid, Lu target

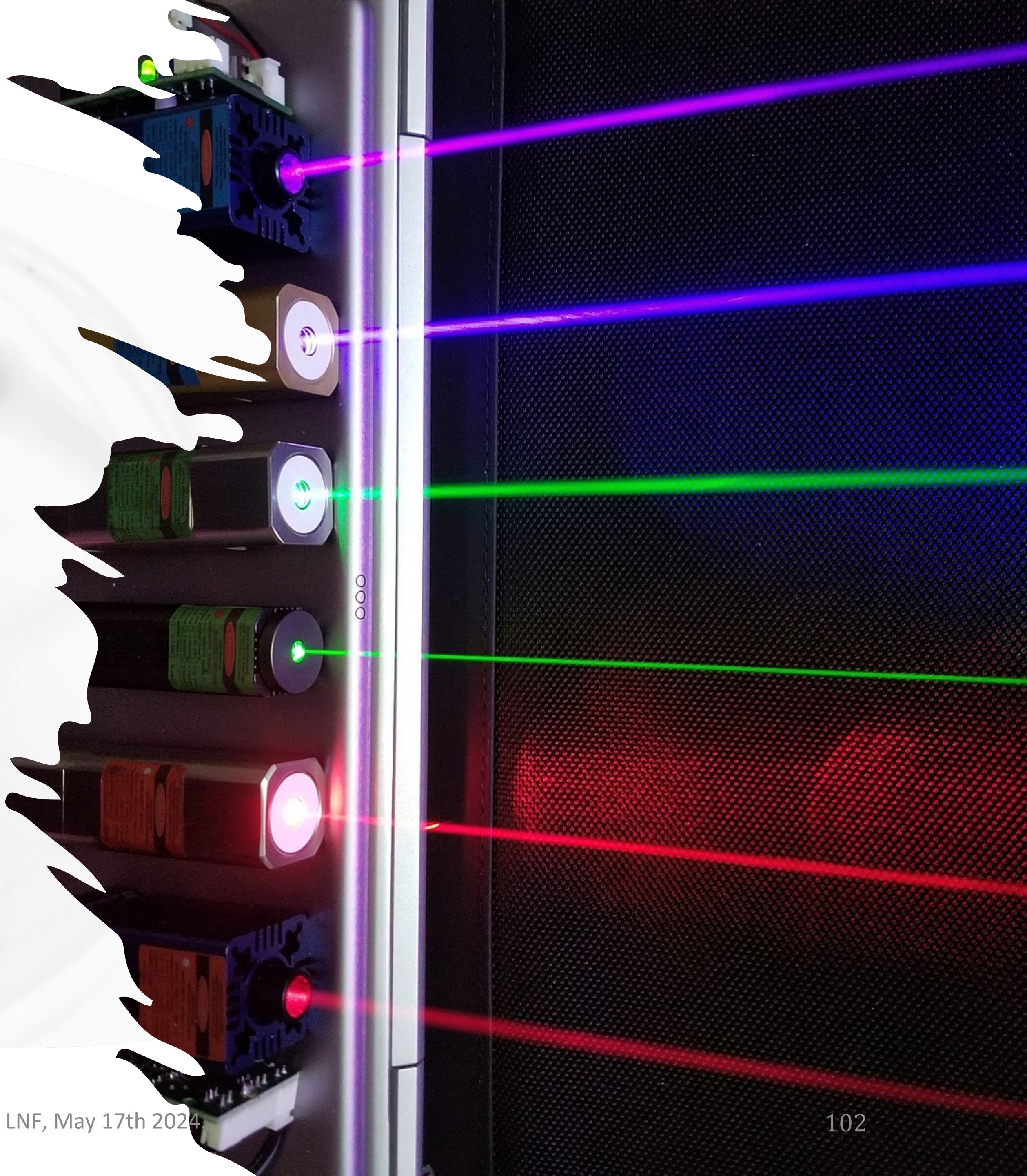
Target choice to be optimized in view of the thermalization goal

Possible choice: non-isotopic cuboids of metallic bulk material (*e.g.*, natural Lu) coated with a layer of at least 200-300 μm of isotopic enriched material

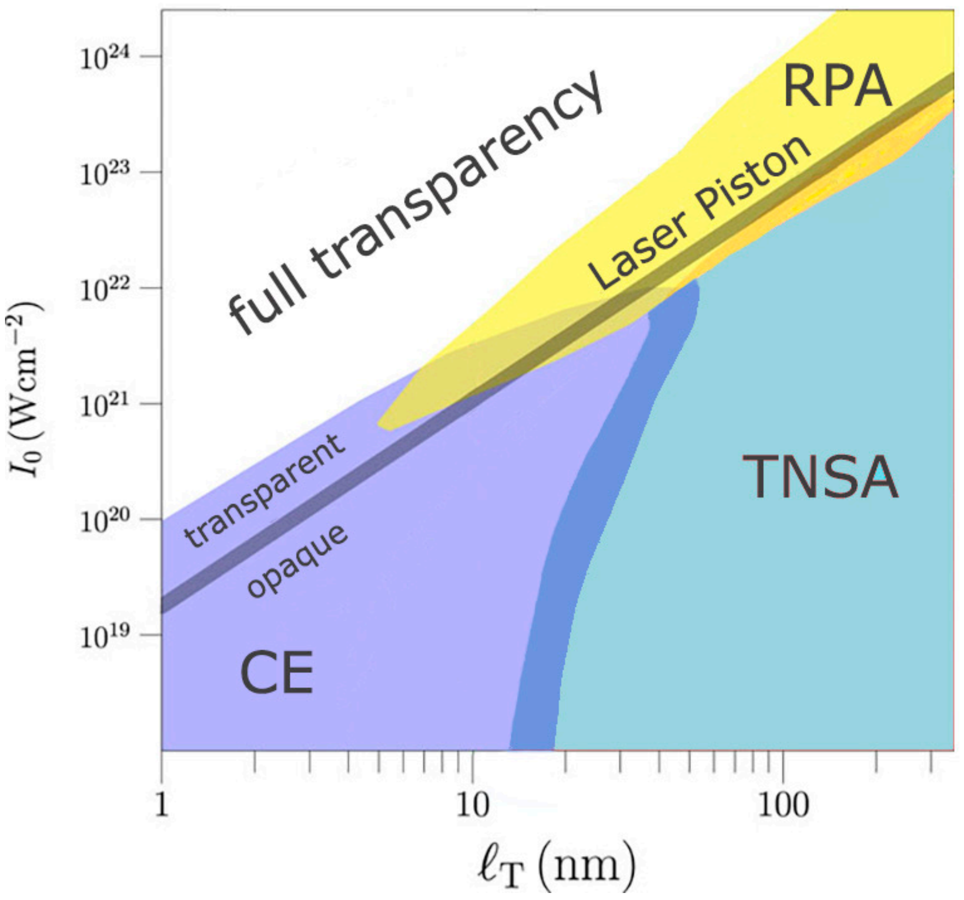
https://www.frontiersin.org/articles/10.3389/fphy.2022.727718/full

CSN3
Fisica
Nucleare

Why laser



Laser-matter interaction

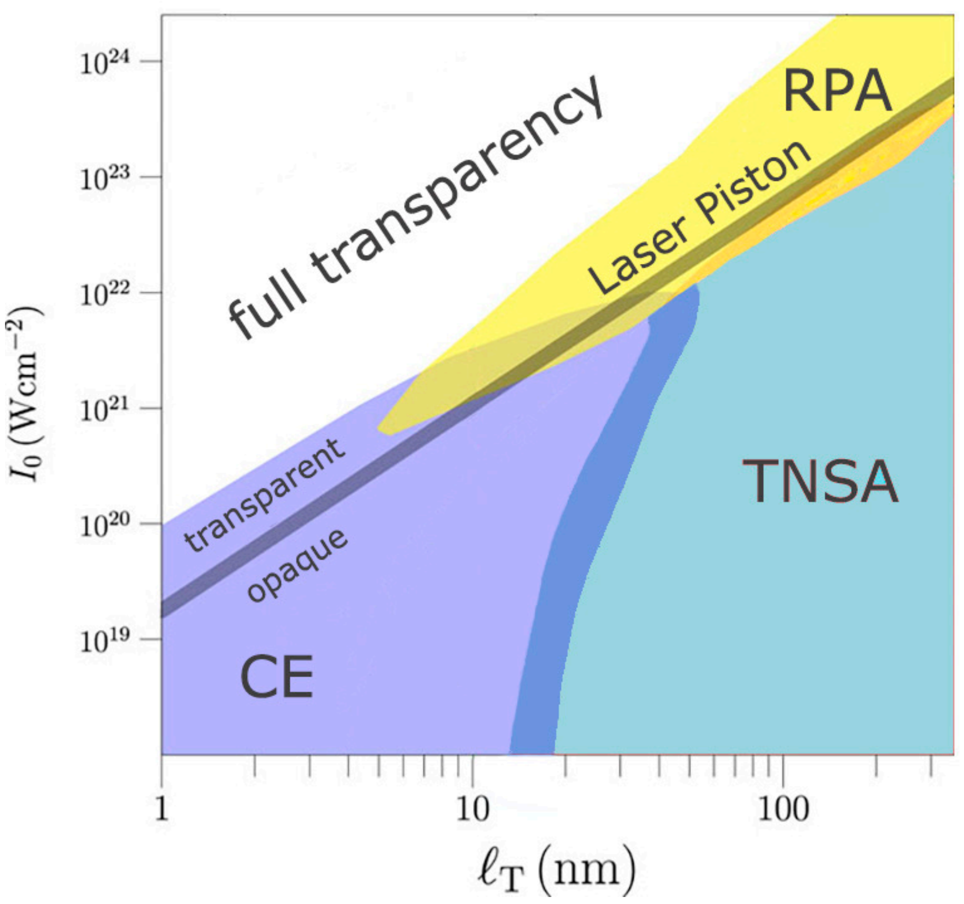


When a high intensity laser pulse (above 10^{18} W/cm^2) is focused in a spot of the order of a few microns on a target placed in vacuum, a plasma consisting of electrons and ions is created almost instantaneously.

- **Target Normal Sheath Acceleration (TNSA):** effective in accelerating protons and light ions → a short laser pulse interacting with the target front surface produces a plasma made of ions and fast electrons.

- **Coulomb Explosion (CE):** optimized for clustered gaseous targets, intensities in the range $10^{18} \div 10^{20}$ W/cm^2 and τ < 200 fs → an explosion may occur due to the intense laser field that, extricating several electrons from the molecule cluster, induces a high level of ionization. Possible also for thin (1-10 nm), solid targets or nano-structured targets

Laser-matter interaction



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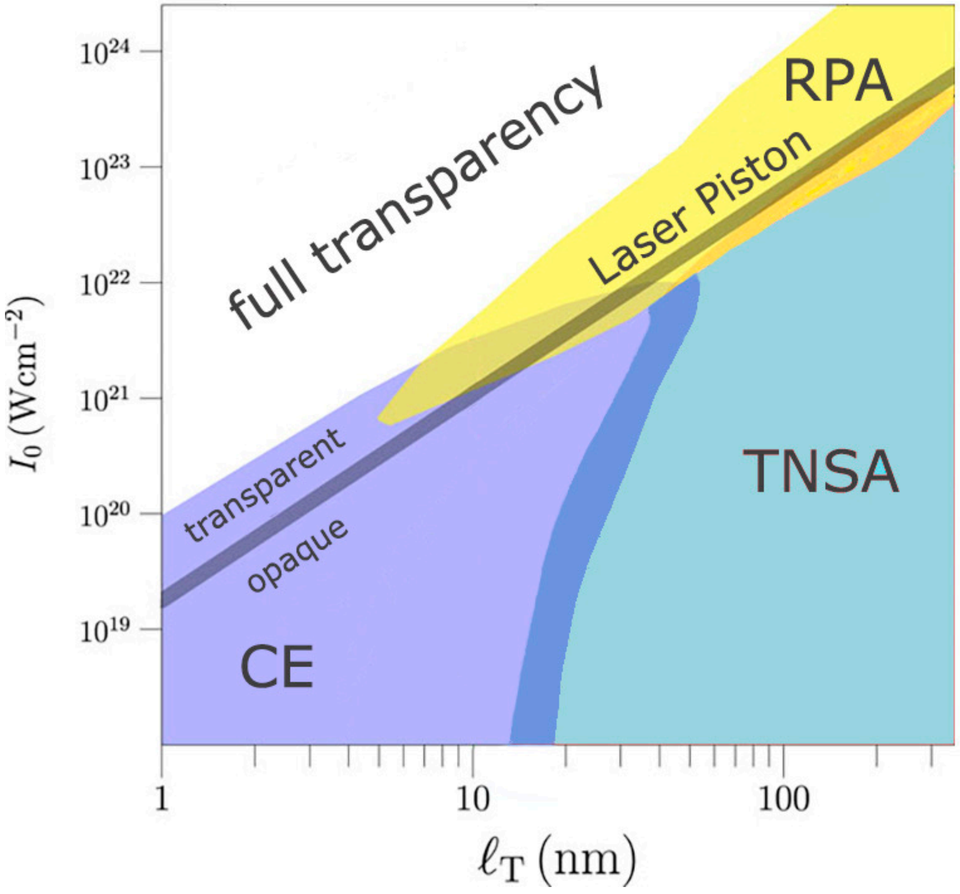
- **Radiation Pressure Acceleration (RPA), or Laser Piston regime:** based on the action of the radiation pressure induced in the interaction of a short laser pulse, of extremely high intensity (above $10^{20} \div 10^{21}$ W/cm^2), with a thin and dense pre-plasma layer created, in front of a target, by the laser-pulse leading edge. The plasma electrons are locally separated from the plasma ions creating a strong accelerating field which efficiently accelerates the ions in the irradiated target area.

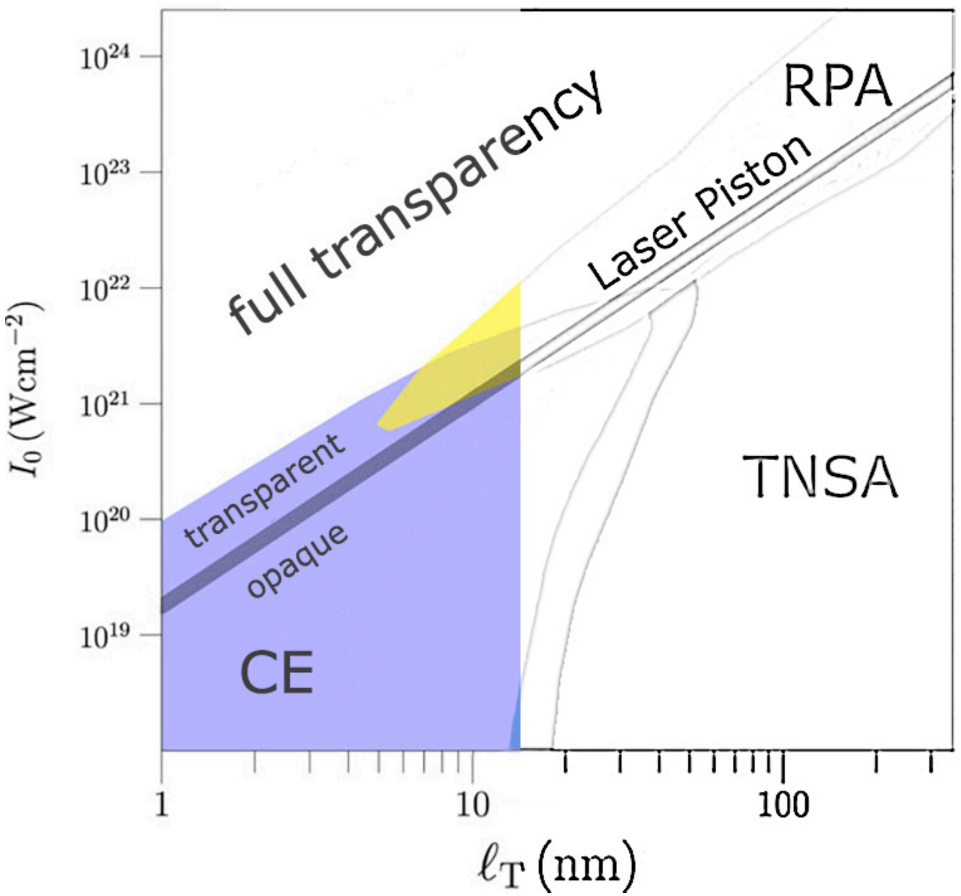
Laser-matter interaction



A precise control of the experimental conditions is challenging with high-power lasers → variations observed between experiments performed in conditions which would seem similar at a first glance.

The scaling of the most important characteristics (such as the energy per particle) with laser and target parameters is still unclear to a large extent, despite the large number of investigations performed.

Experiments at the 10^2 TW regime



Low-density target → one of the most effective way for transferring energy from lasers to a gas target occurs **when the molecules in the gas are organized in clusters**

If the electromagnetic field is strong enough the cluster atoms are ionized, and a Coulomb Explosion can take place.