Fusion - from stars to earth

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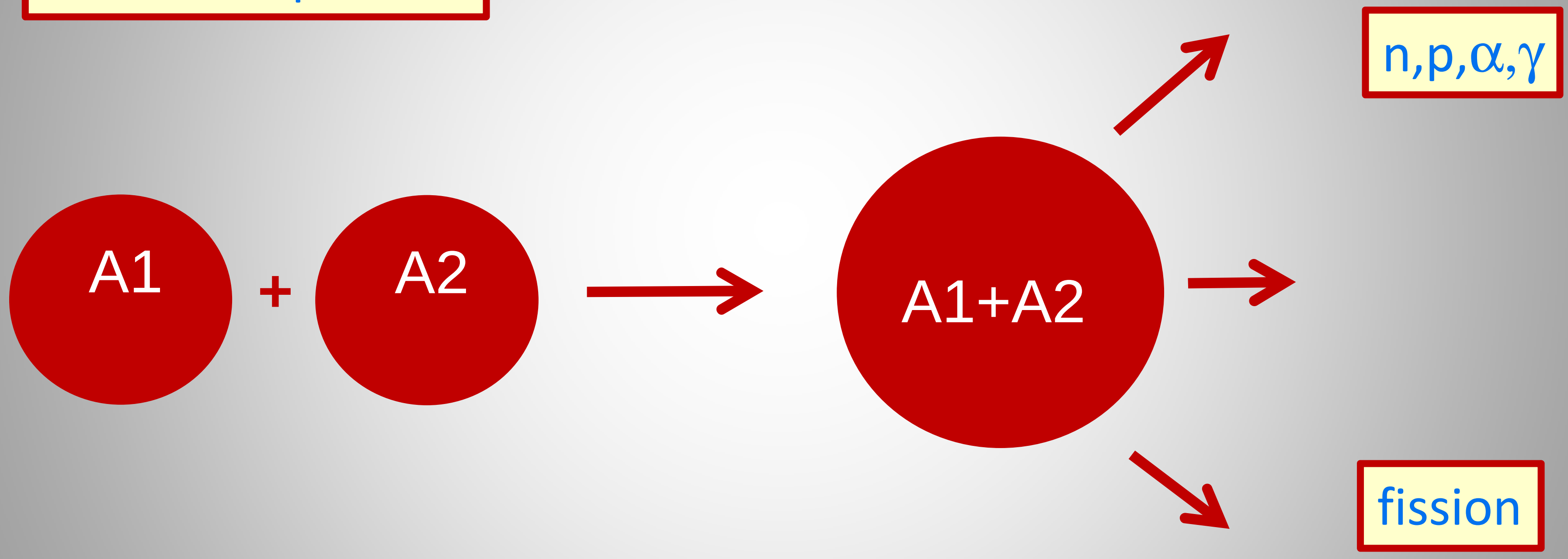
Fusion of two nuclei

The fusion process



Outlook

Nuclear physics and the big bang model

Properties of nuclei “endothermic exothermic,….”

Fusion in the stars

- The LUNA collaboration
- The Wong formula

Fusion of stable heavy ions

- A toy model for understanding CC effects

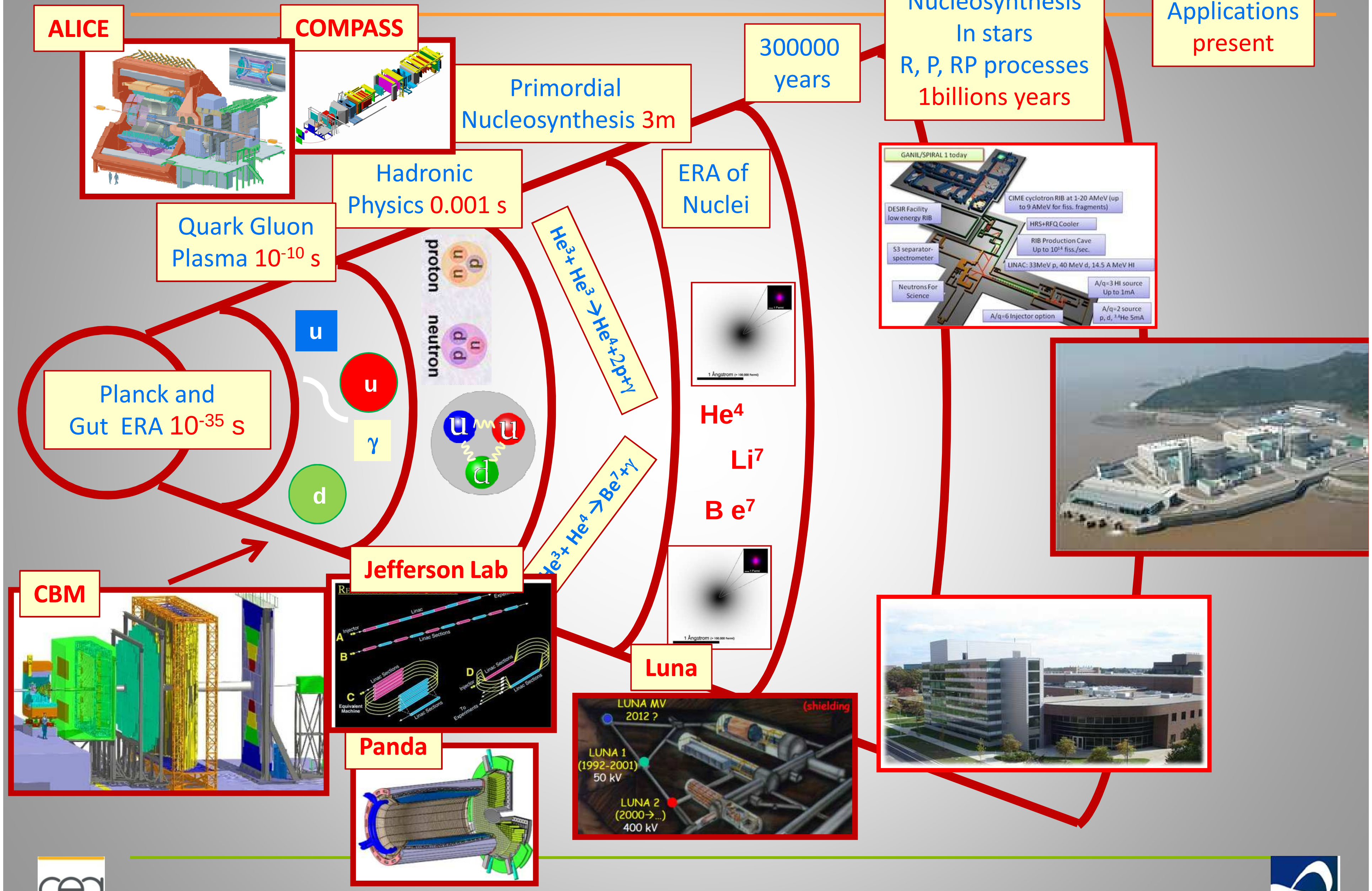
Fusion of exotic nuclei

- The break-up (?)

The ITER project

The future

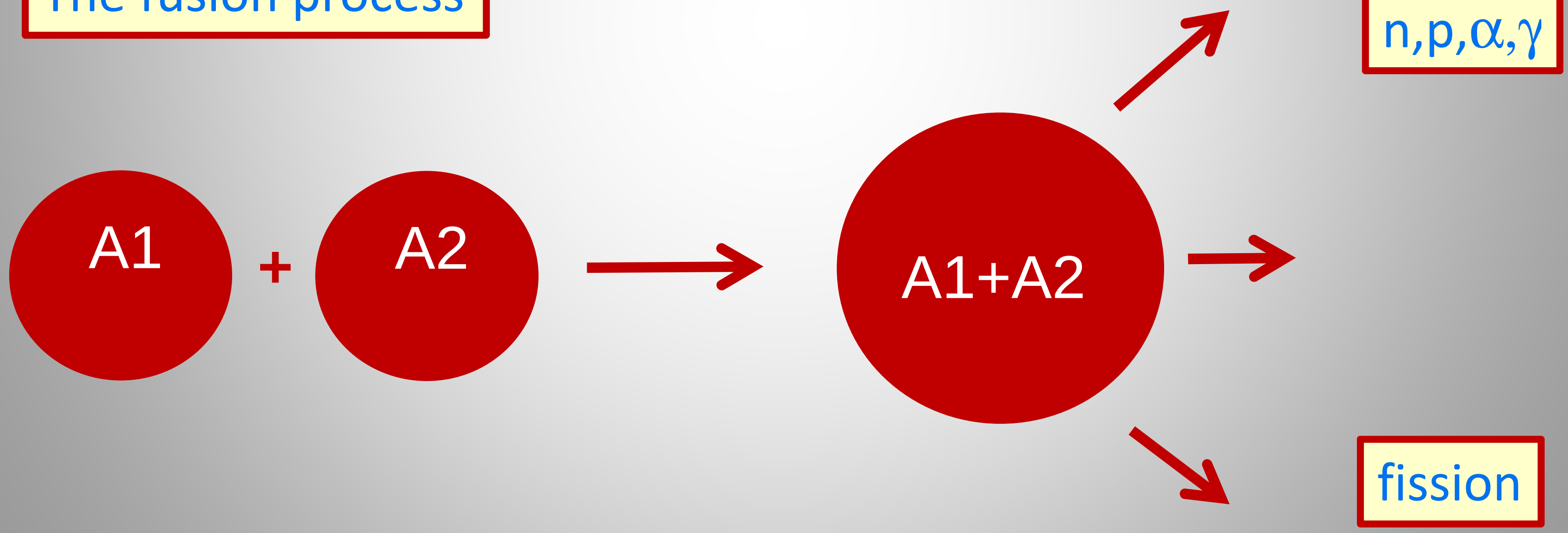
The Nuclear Physics era



Properties of nuclei

If two nuclei A_1 and A_2 fuse to form an $A=A_1+A_2$ nucleus, the reaction is exothermic and energy is released if A<56.
If A>56 then the fusion reaction is endothermic.

The fusion process

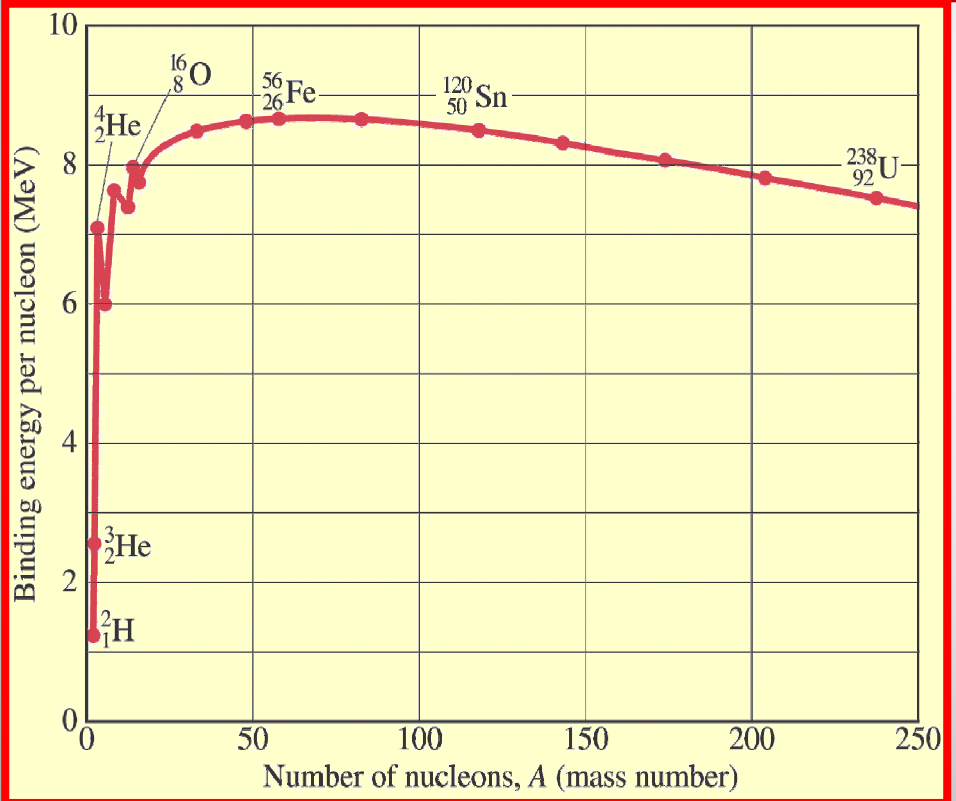


Properties of nuclei

Each Isotope (A,Z), characterized by a mass number A and a charge Z, has in its ground state a rest mass $M_{A,Z}$. This total mass is less than the sum of the masses of the constituent protons and neutrons due to the binding energy of the system.

$$B(A,Z)=(Zm_p+Nm_n-m_{A,Z})c^2$$

B(A,Z)/A



A=N+Z

Properties of nuclei

Two examples of reactions and the energy released:

In the SUN: $p+p \rightarrow d+e^{+}+\nu_e$ **(1)**

ITER Project: $T+d \rightarrow He^{4}+n$ **(2)**

(1): 2x7.289-13.136=1.44MeV That is: **Q=1.44 MeV**

(2): 14,950+13,136-(2.425+8.071)=17.59MeV That is: **Q=17.6 MeV**

Δ (Mass excesses in MeV):

n= 8.071, p=7.289, d=13.136, T=14,950, He^{4}=2.425

The energy of the stars

Fusion is the energy source of the Universe, occurring in the core of stars.

The energy of the stars

What we see as light and feel as warmth is the result of fusion reactions in the Sun: Hydrogen nuclei collide, fuse *into heavier Helium atoms and release tremendous amounts of energy in the process.*

$p+p \rightarrow d+e^{+}+\nu_e$ (Q=1.44 MeV) (1)

However, the average lifetime of protons in the Sun due to the transformations to deuterons by means of the equation (1) is very small of the order of 10^{10}years.

$d+p \rightarrow He^{3}+\gamma$ (Q=5.49 MeV) (2)

At this stage protons are more abundant than deuterons, about one deuteron for every 10^{18} protons.

The energy of the stars

$$He^3 + He^3 \rightarrow He^4 + 2p + \gamma \quad (Q=12.86\ MeV) \quad (3)$$

Or

$$He^3 + He^4 \rightarrow Be^7 + \gamma \quad (Q=1.59\ MeV) \quad (4)$$

The chain of these reactions is called the hydrogen cycle. *The results of this cycle is the transformation of four protons into an a-particle, ^4He nucleus along with two positrons ($2e^+$) and two neutrinos and 26.7MeV of released energy*.

Overall result: $4p \rightarrow He^4 + 2e^+ + 2\nu$

Every second, our Sun turns 600 million tons of Hydrogen into Helium, releasing an enormous amount of energy

The energy of the stars

What about these reactions? Do they contribute?

$$p + He^3 \rightarrow Li^4 + \gamma \quad \text{and} \quad d + d \rightarrow He^4 + \gamma$$

What happens to the Be^7?

Chain II

$$Be^7 + e^- \rightarrow Li^7 + \nu_e$$

$$Li^7 + p \rightarrow 2He^4$$

Chain III

$$Be^7 + p \rightarrow B^8 + \gamma$$

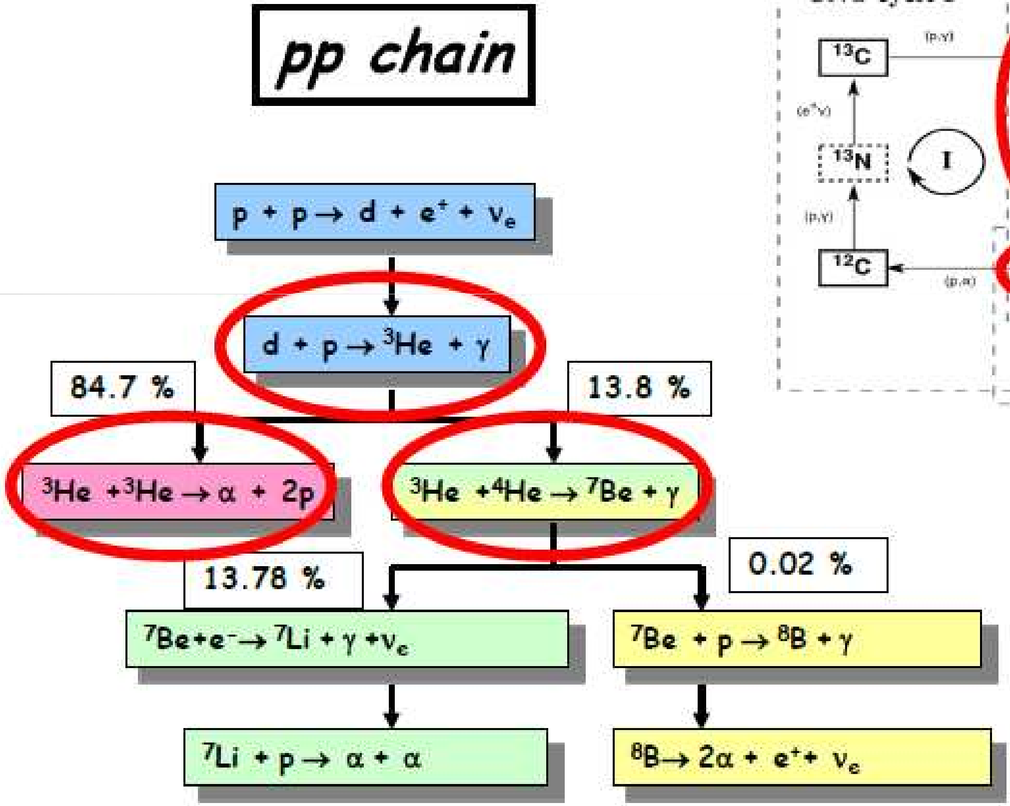
$$B^8 \rightarrow Be^8 + e^+ + \nu_?$$

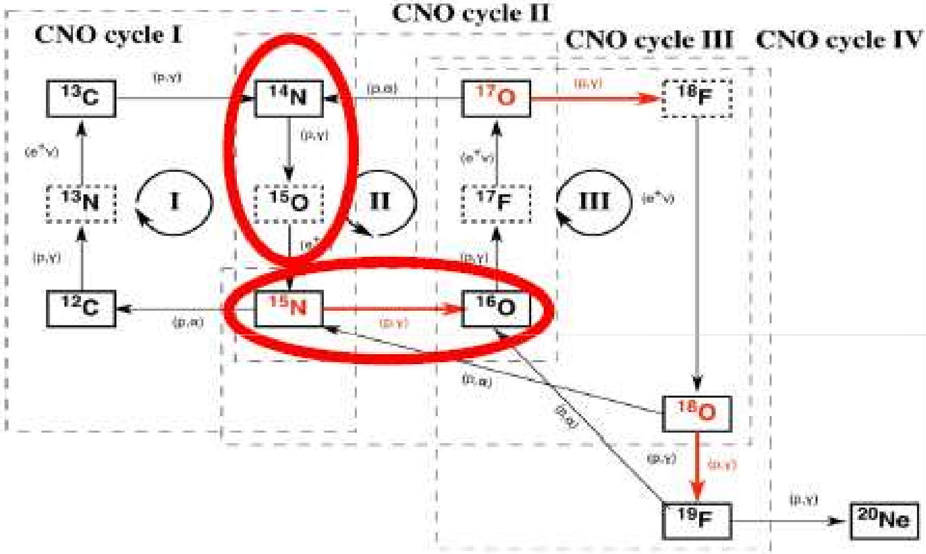
$$Be^8 \rightarrow 2He^4$$

The energy of the stars

Hydrogen burning

Produces energy for most of the life of the stars





Guglielmetti for the LUNA Collaboration EPJ Web of Conferences Vol. 17 (2011)5th

$$4p \rightarrow {}^4He + 2e^+ + 2\nu_e + 26.73\ MeV$$

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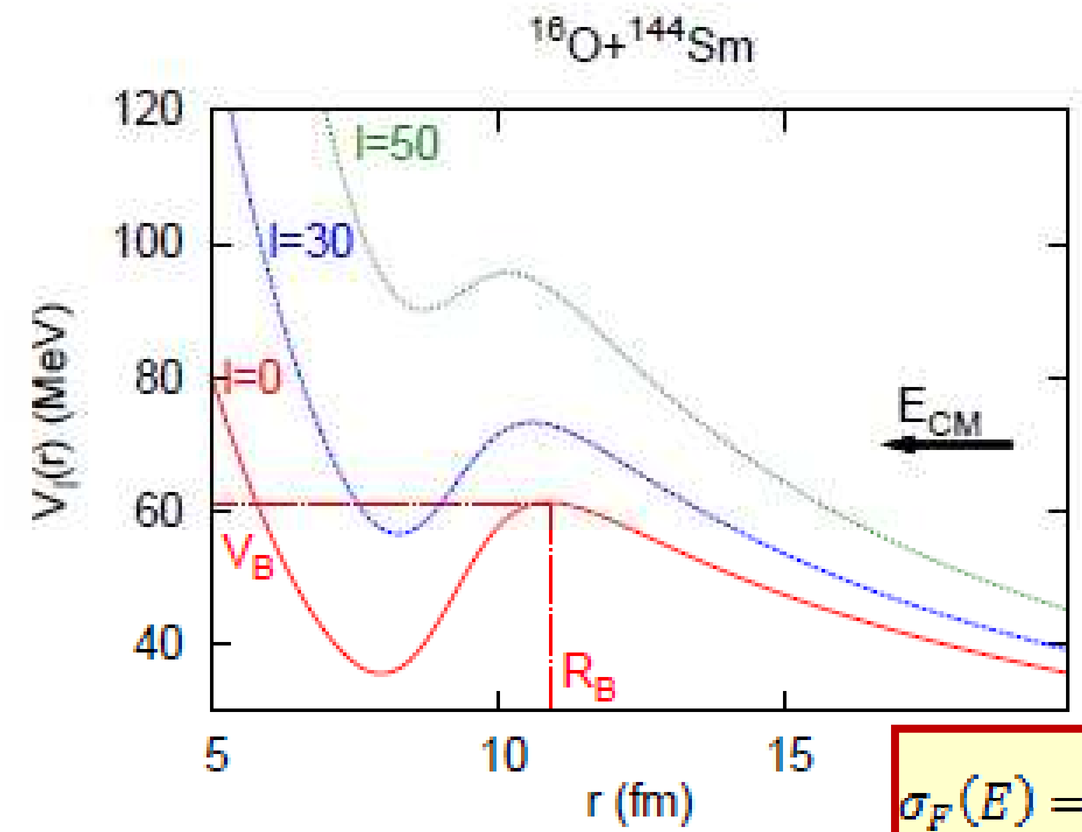
The Wong formula

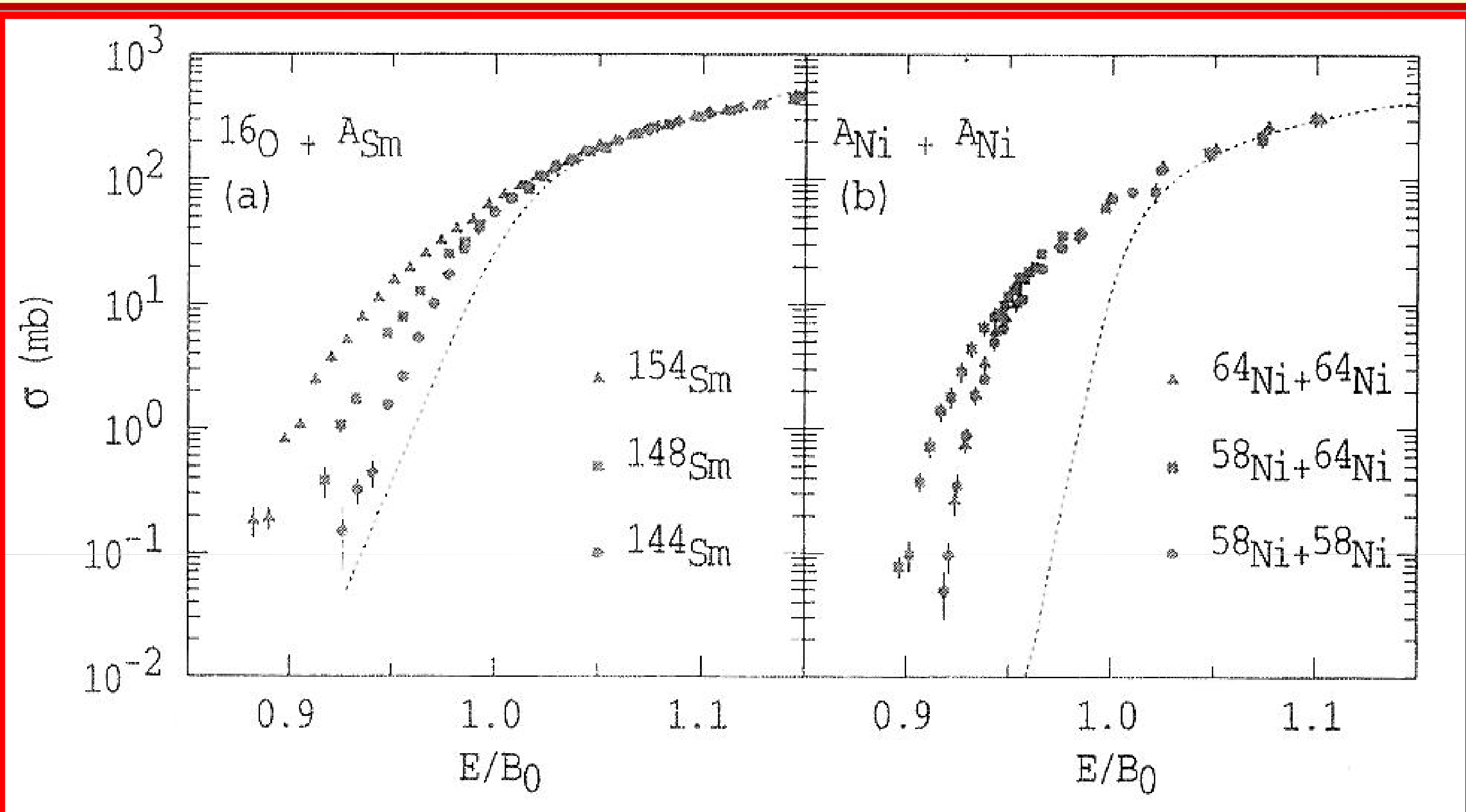


$$\sigma_F(E) = \frac{\hbar\omega R_B^2}{2E} \ln\left[1 + \exp\left[\frac{2\pi}{\hbar\omega}(E - V_B)\right]\right]$$

Where the height of the s-wave barrier is V_B, R_B is the radius to the maximum of the barrier and $\hbar\omega$ is the curvature of the barrier

C. Y. Wong PRL 31 766 1973

Fusion of stable nuclei



- Fusion excitation functions for ^{16}O on Sm isotopes show a marked increase of cross section with increasing mass and deformation.
- Fusion cross section for Ni isotopes indicate that inelastic channels and transfer of nucleons may affect the fusion process.

M. Dasgupta et al., Annu. Rev. Nucl. Part. Sci. 1998. 48:401-61

Fusion of stable nuclei

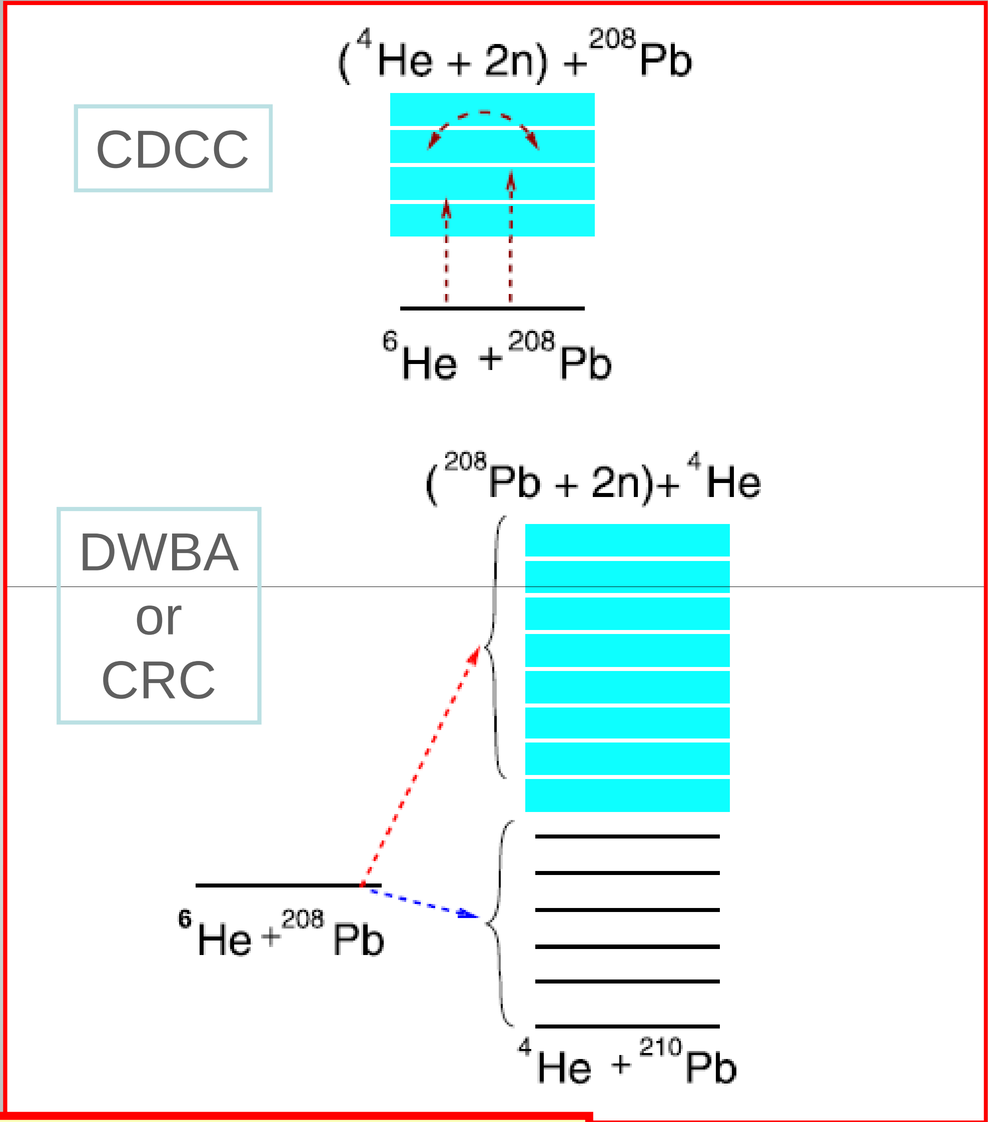
Coupled-channel effects in sub-barrier fusion cross-section

A natural way to take into account the structure of the colliding nuclei is to calculate the fusion cross section in the frame work of the coupled-channel scattering formalism. The fusion cross section is expressed as the difference between the reaction cross section and the cross section of inelastic or transfer channels:

$$\sigma_f(E) = \frac{\pi}{K^2}\sum_{l}(2l+1)(1-|S_l|^2) - \sum_{inel}\sigma_{inel}$$

Where $|S_l|^2$are the elastic scattering elements? (This point has to be discussed).

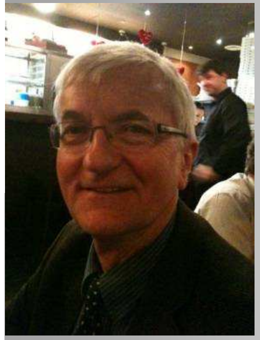
CRC, CDCC methode



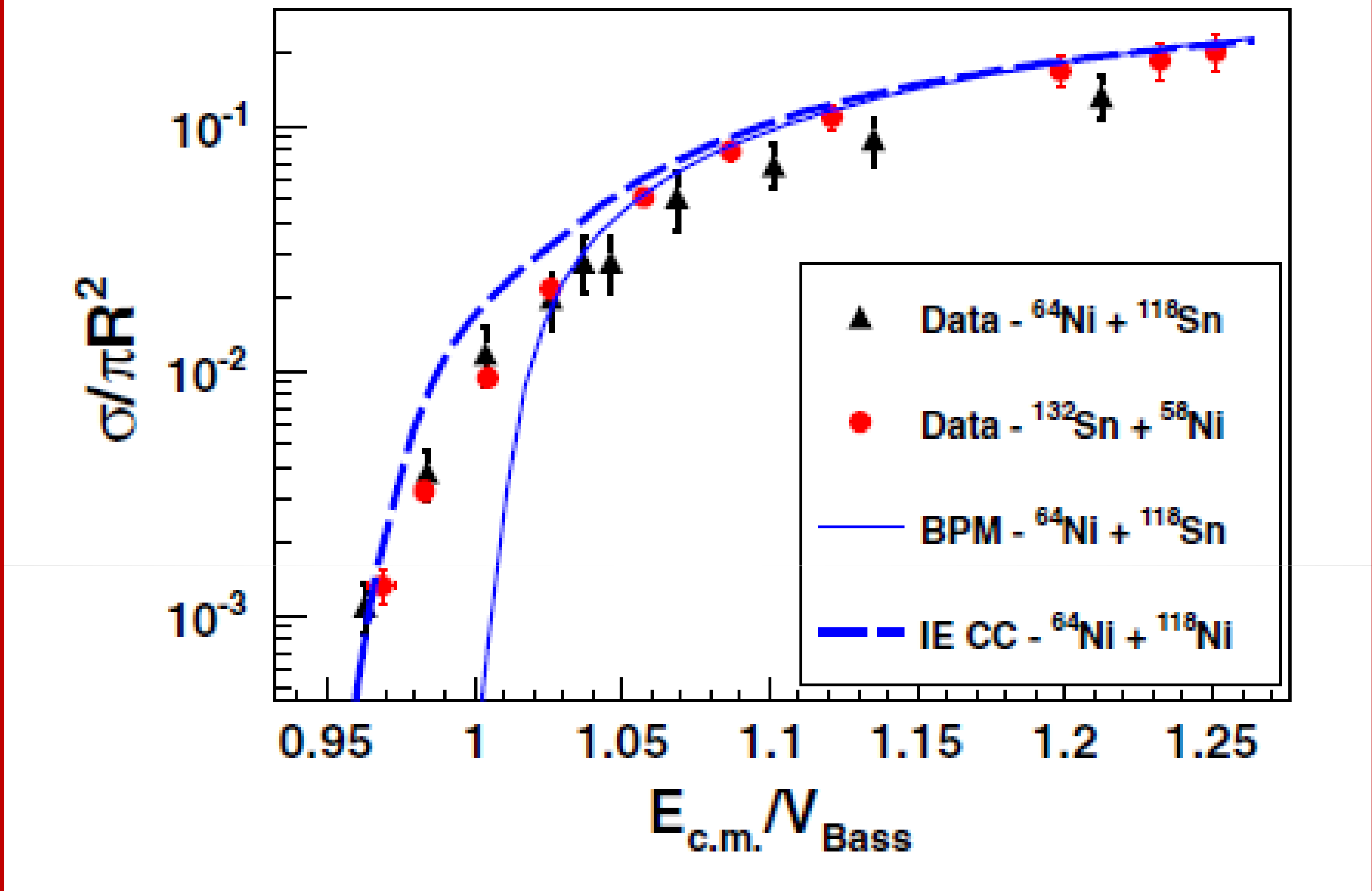
J.P. Fernandez-Garcia et al., PLB693 310 (2010))

CRC, CDCC methode

Article by F. Nunes
http://www.scholarpedia.org/article/Continuum-Discretised_Coupled_Channels_methods



Fusion of stable nuclei



Reduced fusion excitation functions for $^{64,58}Ni + ^{118,132}Sn$ compared with the one barrier penetration model and coupled channel calculations (CC) including inelastic excitations.

Z. Kohley et al, PRL 107 202701 2011

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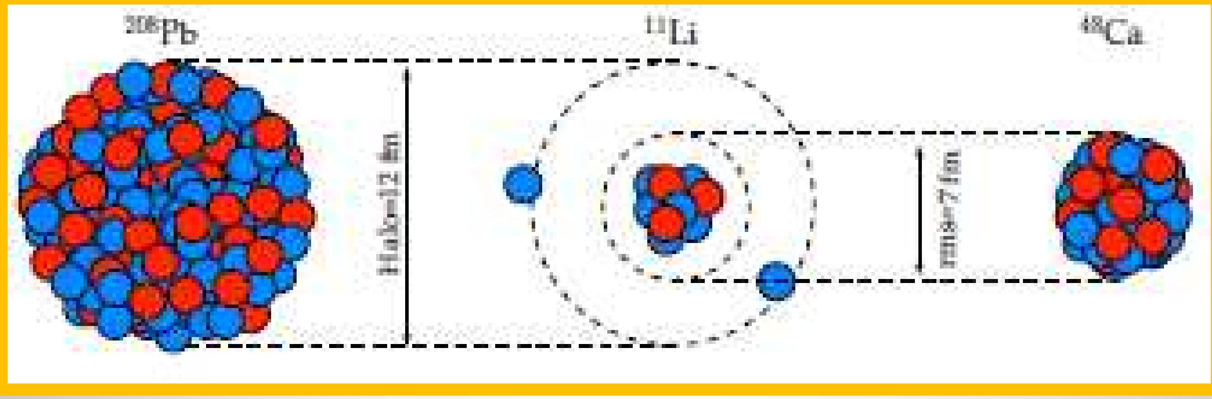
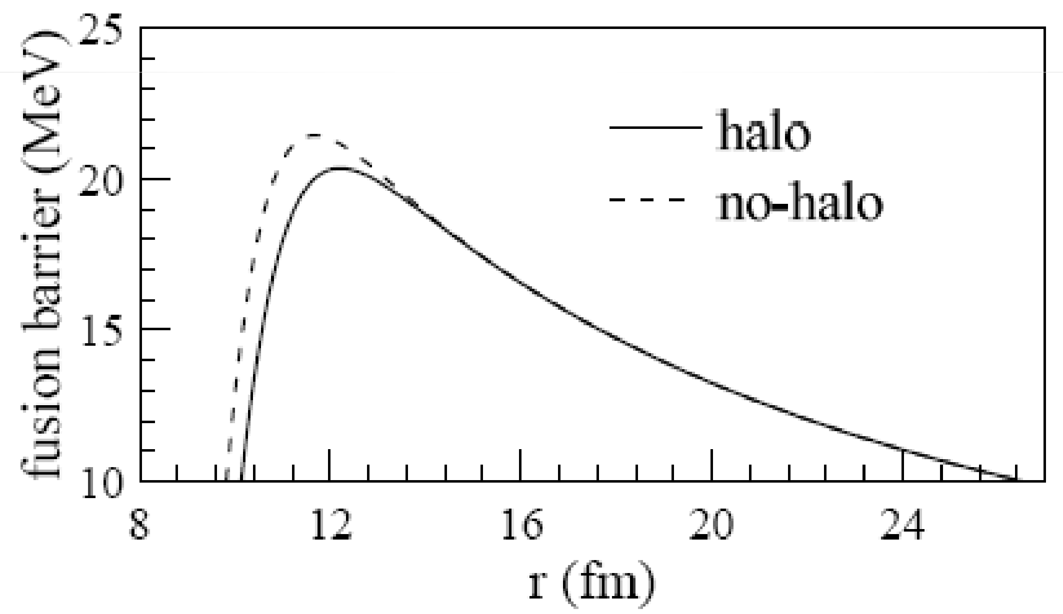
Fusion of stable and exotic nuclei

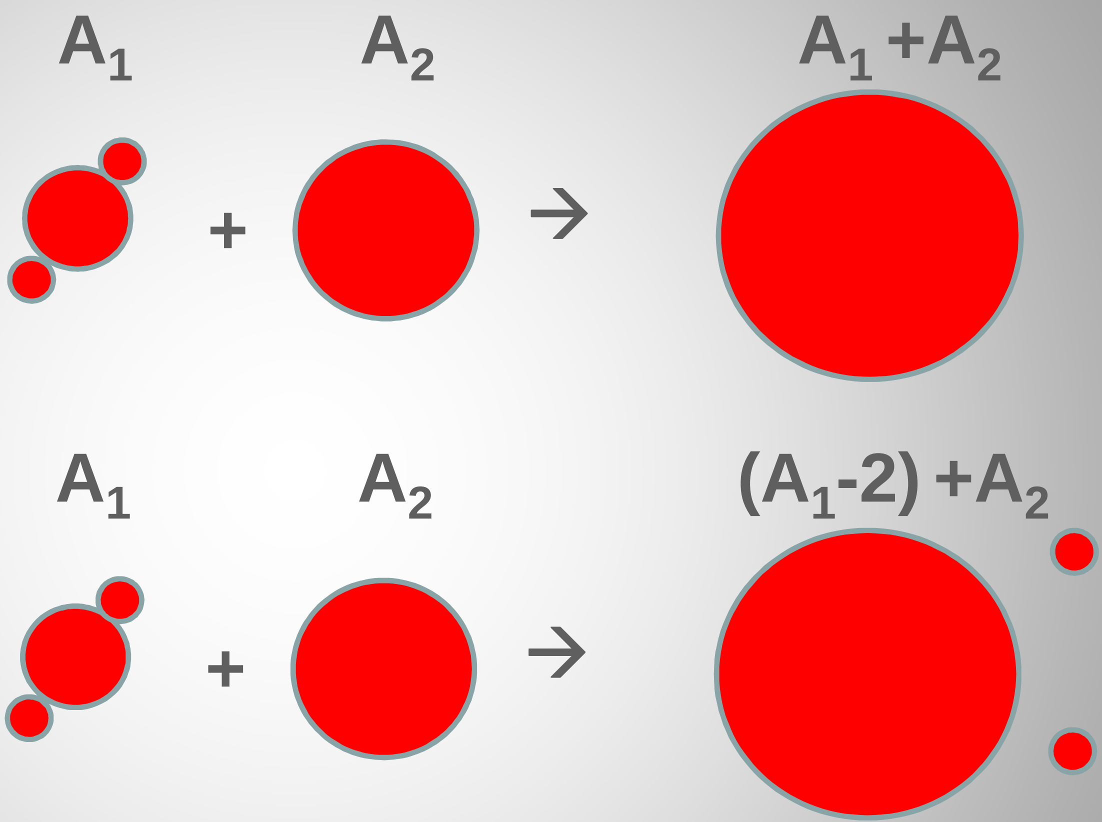




Complete and Incomplete fusion

Complete fusion

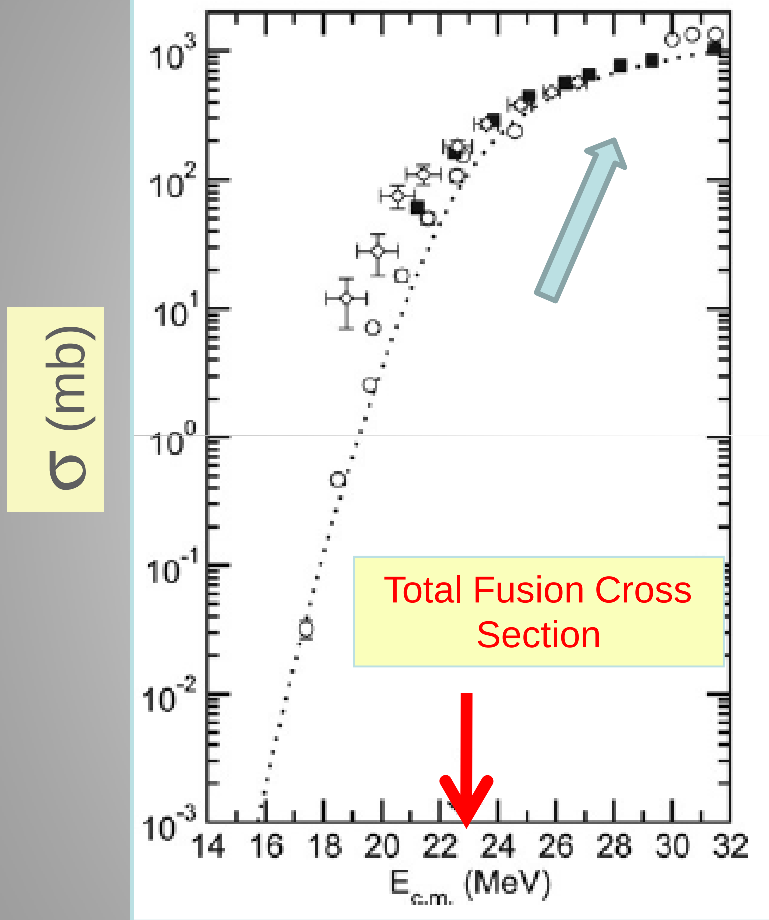
Incomplete fusion



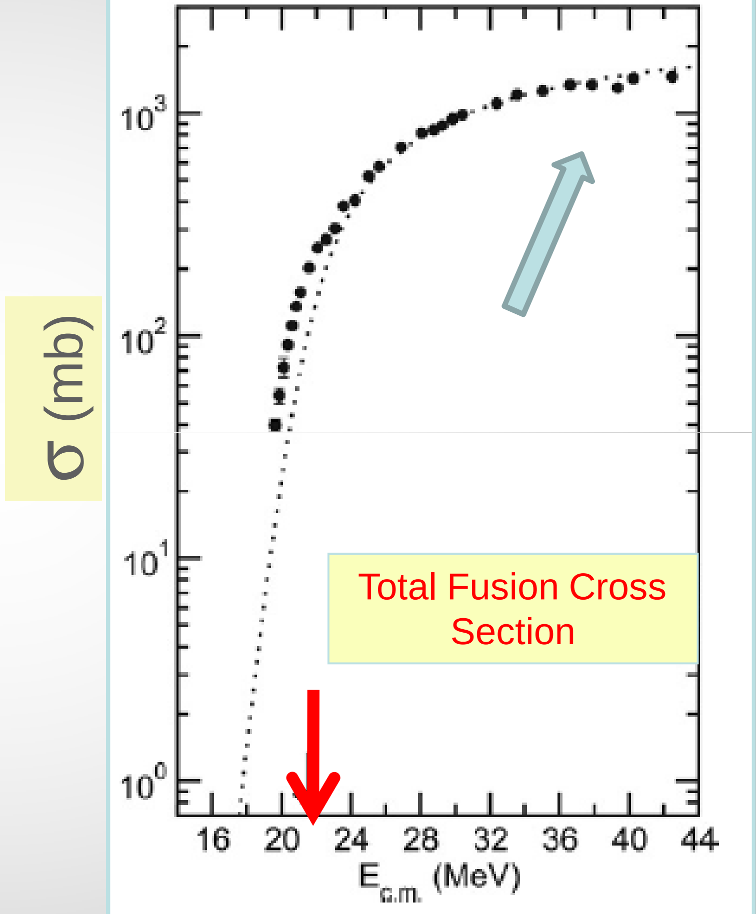
Total fusion = Complete fusion + Incomplete fusion

Results and discussion

$^4He+^{238}U$



$^4He+^{209}Bi$



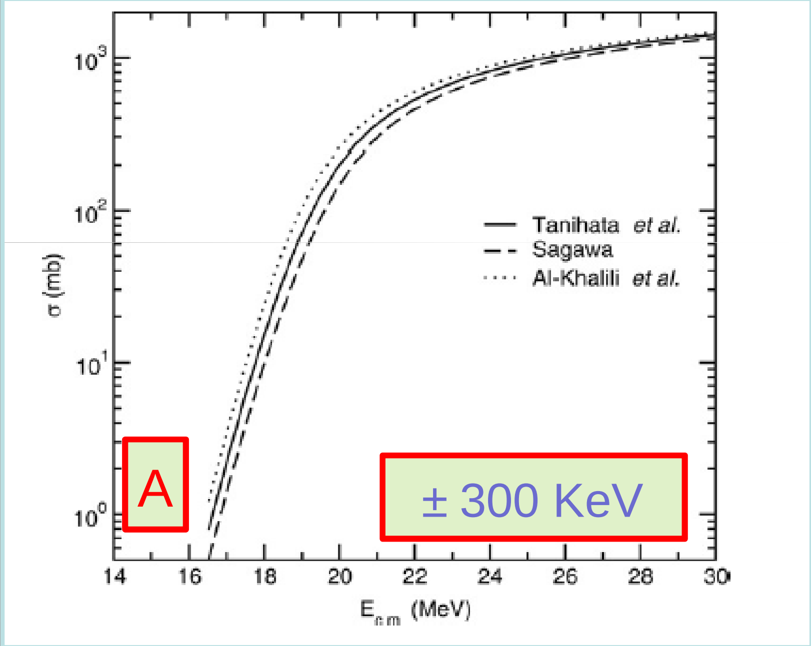
N. Keeley, R. Raabe, N.Alamanos, J.L. Sida, Prog. Part. Nucl. Phys. 59, 579 (2007)

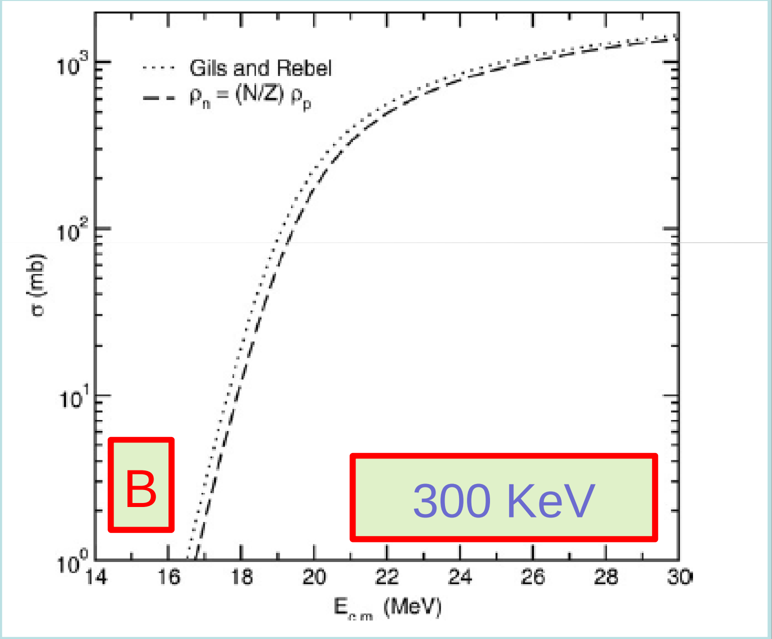
Conditions for the calculations

For the calculations we have used M3Y potentials and the IWBA approach.

A. $^{6}He+^{208}Pb$ fusion excitation function calculations employing different densities.

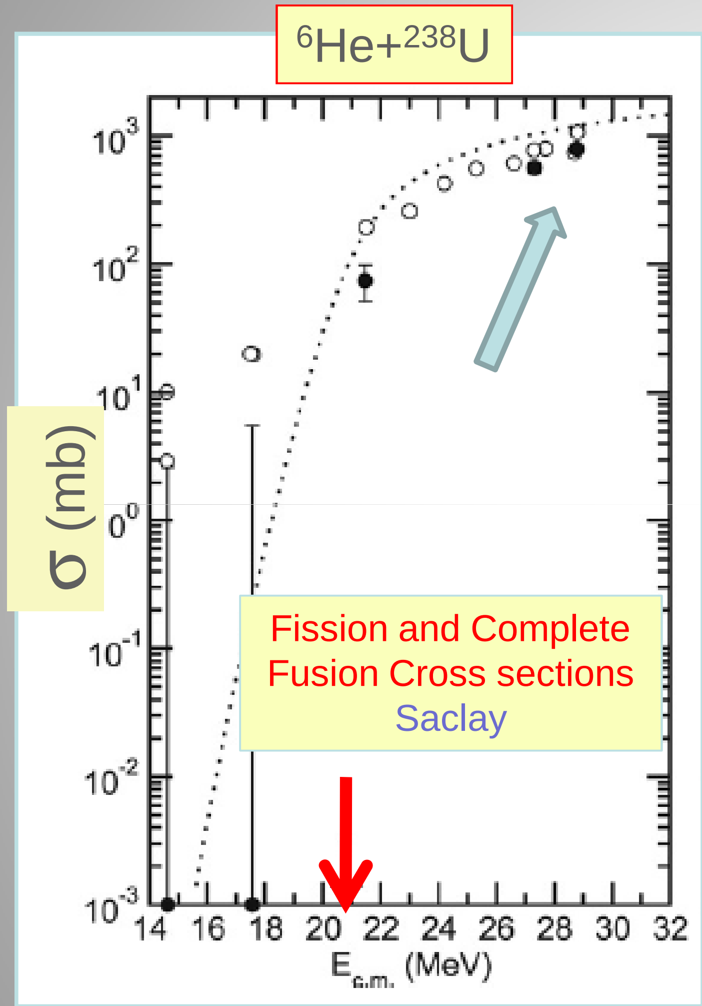
B. $^{6}He+^{208}Pb$ fusion excitation function calculations employing different neutron densities

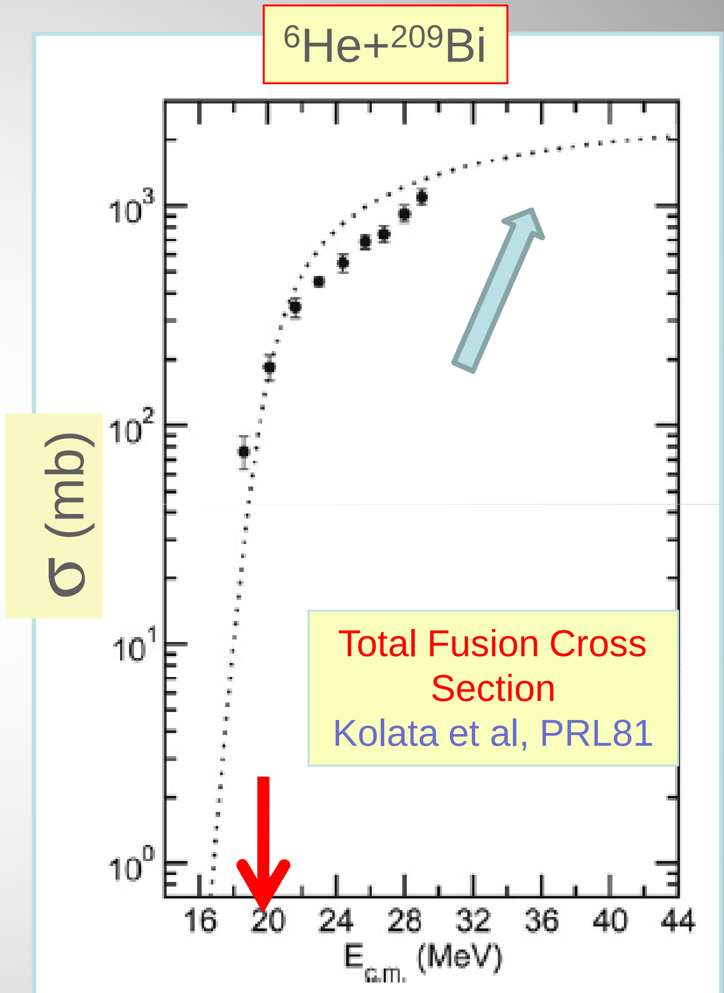




The overall level of uncertainty is a shift in energy of the order of 1 MeV of the calculated fusion excitation function.

Results and discussion



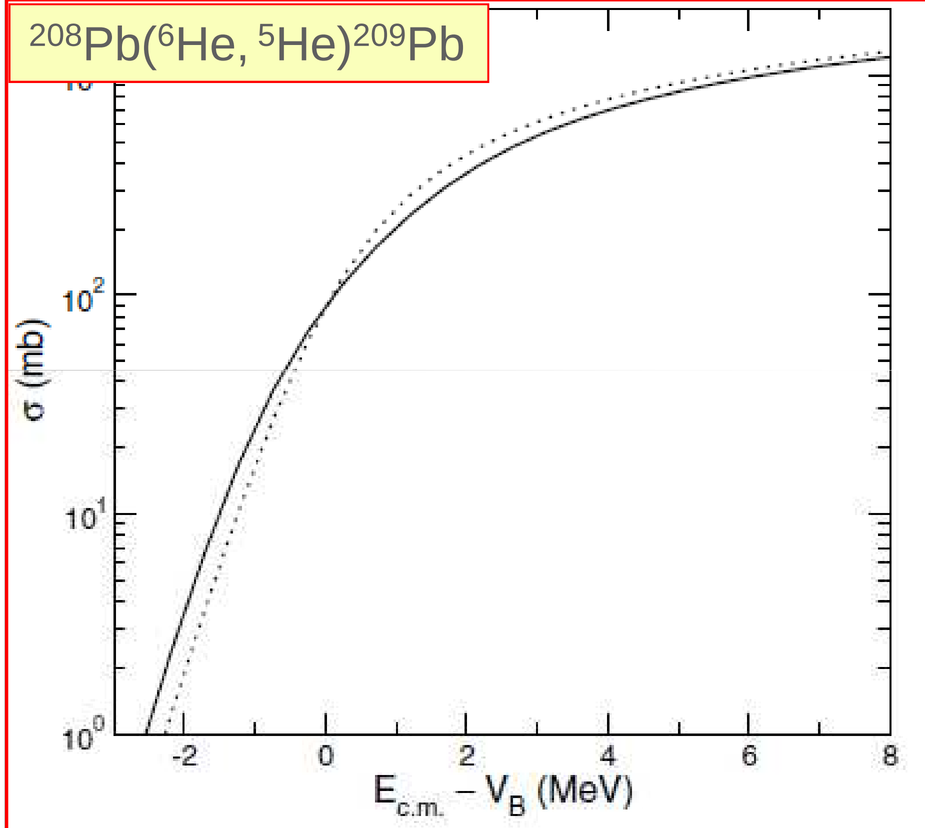


N. Keeley, R. Raabe, N.Alamanos, J.L. Sida, Prog. Part. Nucl. Phys. 59, 579 (2007)

Results and discussion

The fusion cross section suppression at above barrier energies is partially due to multi- nucleon transfer reactions

$^{208}Pb(^{6}He, ^{5}He)^{209}Pb$



What about two neutron transfer?

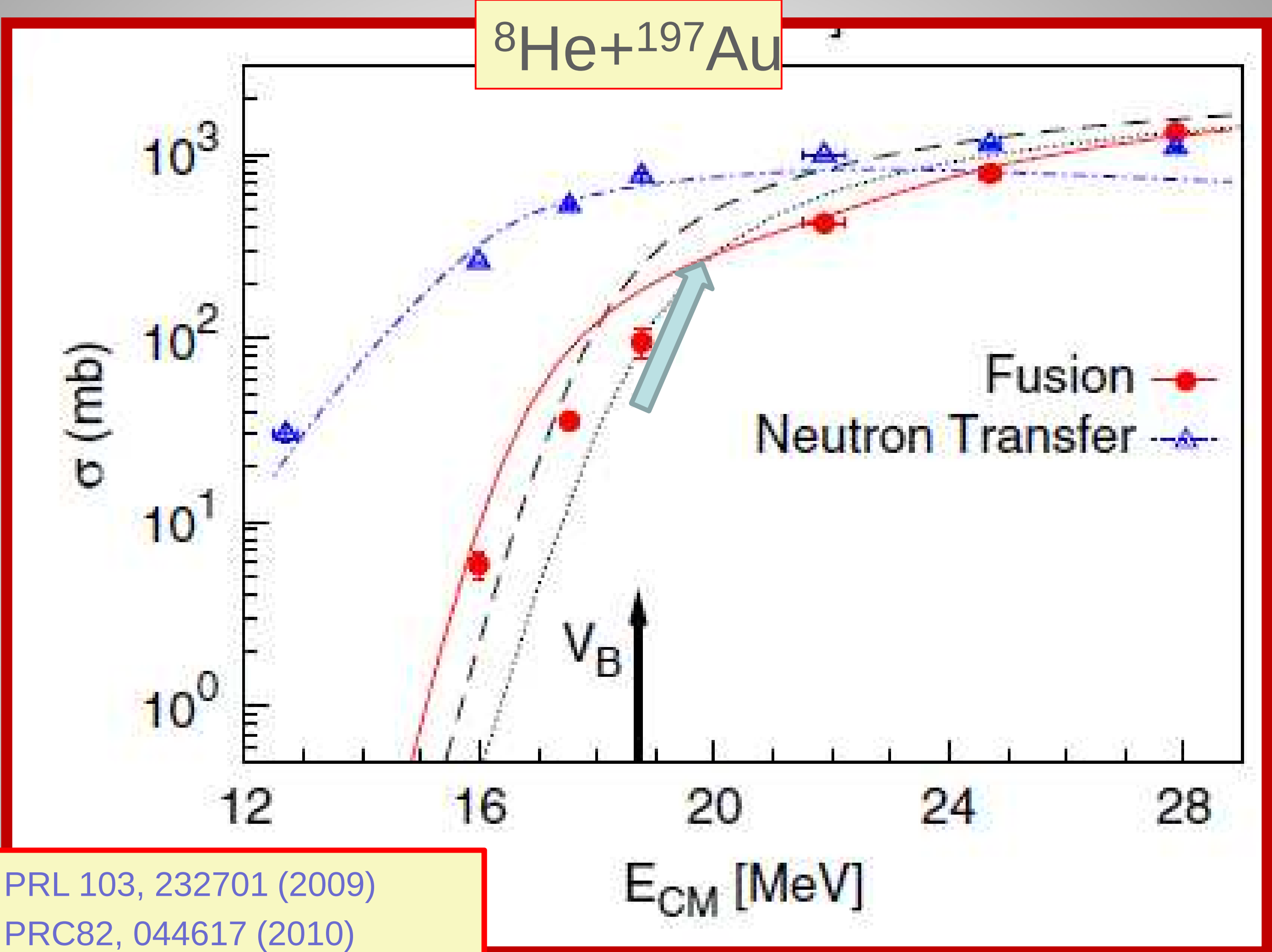
In some cases lack of knowledge of the requisite nuclear structure.

(two step versus direct di-neutron transfer?)

But we can calculate di-neutron transfer

N. Keeley and N. Alamanos PRC77 054602 (2008)
N. Keeley and N. Alamanos PRC75 054610 (2007)

New results for $^{8}He+^{197}Au$



Lemasson et al. PRL 103, 232701 (2009)
Lemasson et al. PRC82, 044617 (2010)

Article by S. Gales http://www.scholarpedia.org/article/The_GANIL_facility

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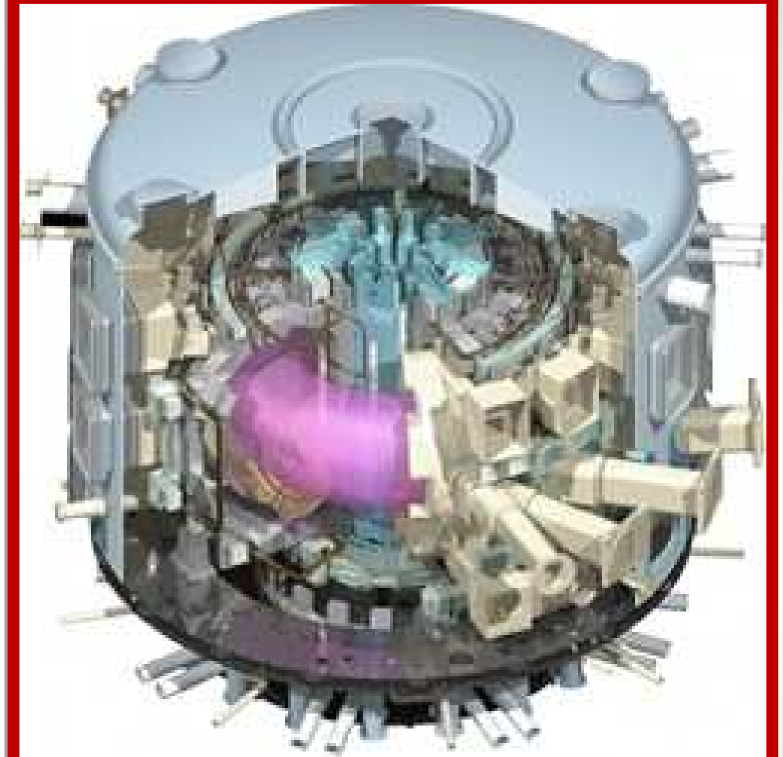
2) b) The ITER Project

$T+d \rightarrow He^4+n+17{,}6$ MeV



A cut-away view of the ITER Tokamak, revealing the donut-shaped plasma inside of the vacuum vessel.

The T-d fusion reaction produces *<u>the highest energy gain at the 'lowest' temperatures</u>*. *It requires nonetheless temperatures of 150,000,000° Celsius to take place - ten times higher than the H-H reaction occurring at the Sun's core.*

In ITER, the fusion reaction will be achieved in a **tokamak** device that uses magnetic fields to contain and control the hot plasma.

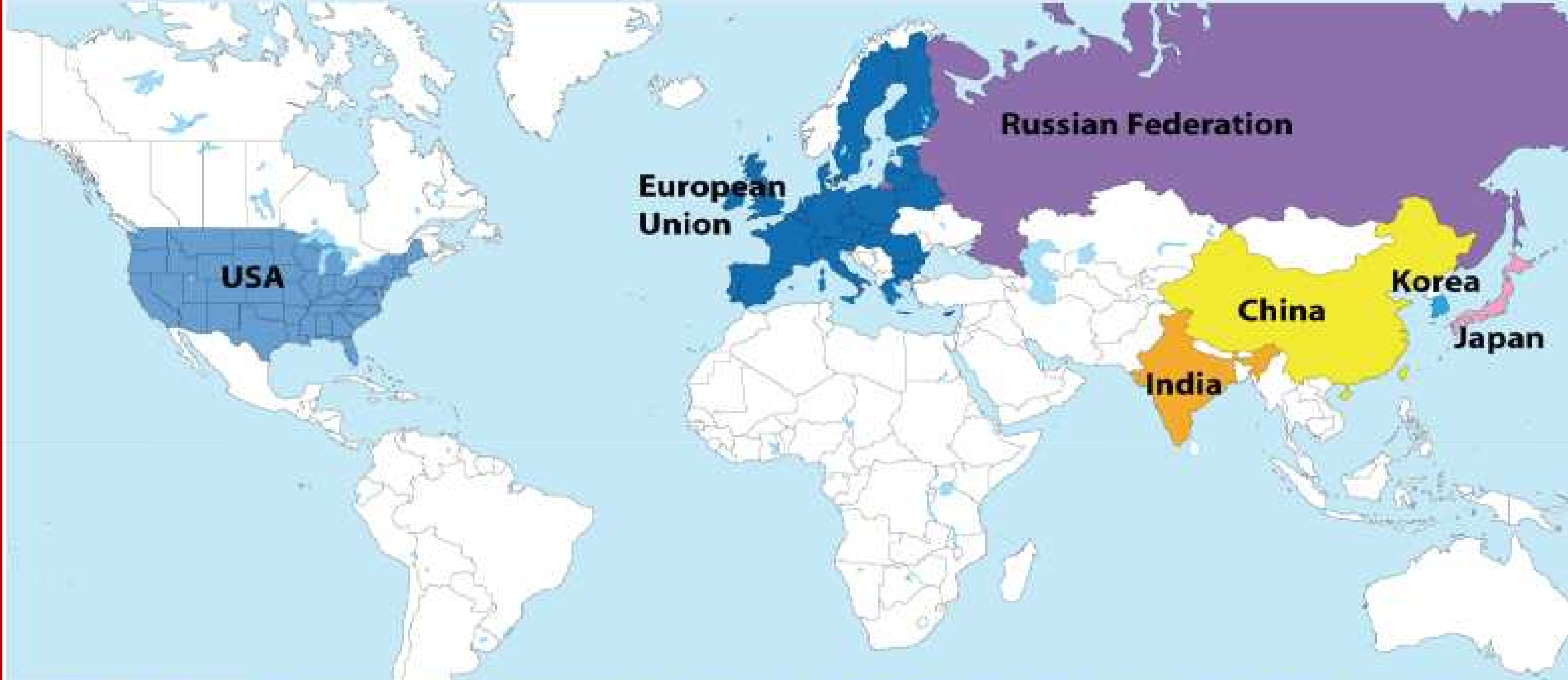
The ITER Project

The scientific goal of the ITER project: to deliver ten times the power it consumes.

Some 80 percent of the energy produced is carried away from the plasma by the neutron which has no electrical charge and is therefore unaffected by magnetic fields

From 50 MW of input power, the ITER machine is designed to produce 500 MW of fusion power—**the first of all fusion experiments** to produce net energy.

ITER:
a truly international cooperation

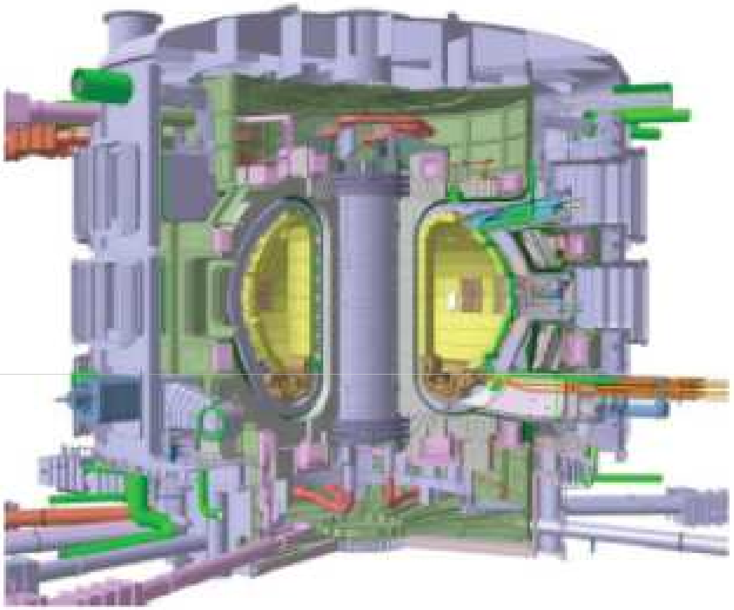


The seven parties involved in the ITER construction represent more than 50% of the world's:

Europe (+ Switzerland) , China, India, Japon, Russian Federation, South Korea, United States of America.

Association
Euratom-CEA

The mass of ITER…



ITER Machine mass:
~23000 t
28 m diameter x 29 m tall

Charles de Gaulle mass:
~38000 t (empty)
856 ft (261 m) long
(Commissioned 2001)

10-year construction sharing

Overall sharing:

EU 5/11, other six parties 1/11 each. Overall contingency of 10% of total.

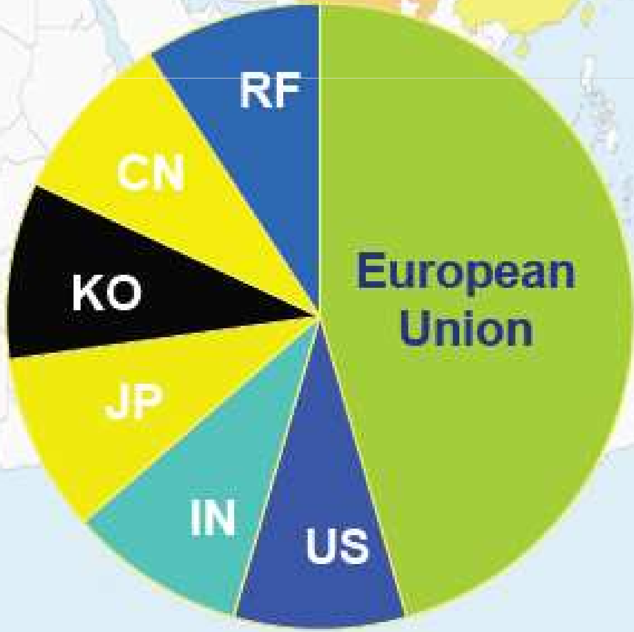
Total amount (European estimation):

15000 million Euro

Procurement : 80%

Staff: 10%

R&D: 10%



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