PolFusion: Polarized Fuel for Fusion

From the point of view of the nuclear physics, the use of **polarized fuel** is the viable way in order to fulfill the requirements for energy production:

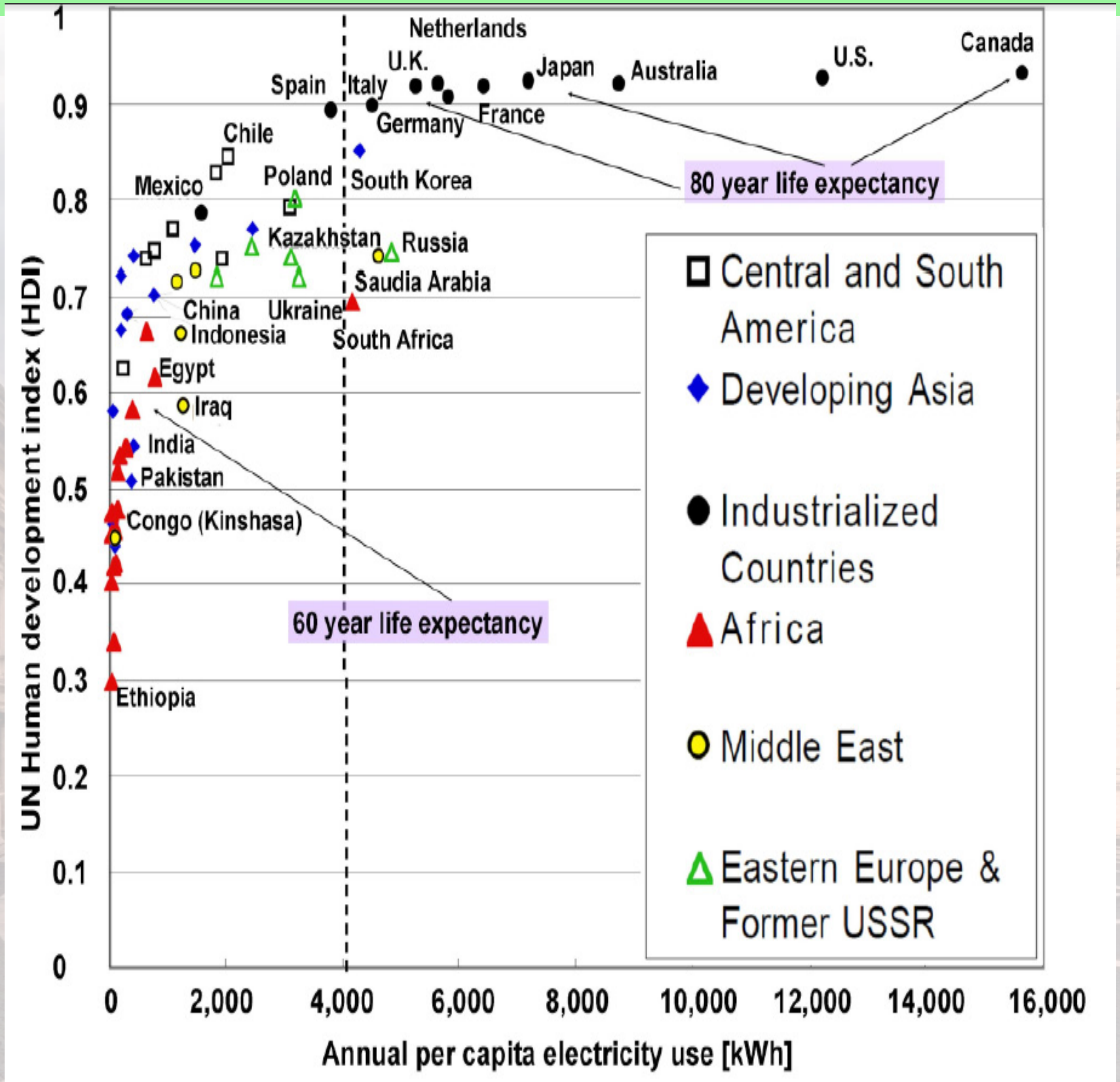
- **enhancement** on fusion **cross section**,
- **control** on angular distribution of **reaction products**,
- possible **neutron lean** reactors.

Practical use is still far away, mainly due to still open questions and requirements:

- polarized fuel, high P and ρ ($P\rho$ two or three order of magnitude **higher**).
- **Preparation** of fuel for magnetic confinement or inertial confinement.
- **Survival** of polarized fuel in fusion environments.

It's a **challenging** deal providing **useful polarized fuel** for the purpose of testing it in present (... future) **Fusion** reactors

Quality of life requires electrical consumption



Developping world (5 billion people) is crawling up UN HDI (United Nation Human Development Index).

The main energy resource in the past few centuries **fossil fuel**.

World Energy Scenario (1996), from World Energy Council (WEC), Internation Energy Agency (IEA) and other international organizations estimate
Coal 230 year, **natural gas 63**, **oil 44 years**.
2013 new report and suggested scenario (Jazz or Symphony).

Total resource based also in non conventional gas and oil extraction, estimation extended to … 100 years.

"Fusion Physics" ed. IAEA Vienna 2012

From WEC (World Energy Council) reports

- Fossil fuel ⟹ global warming
- Depleting only coal ⟹ largest emitter of CO_2
- Oil and gas reserves: tens of years and ⟹ political & military conflits
- Development of fission nuclear reactors ⟹ pubblic opposition, proliferation, radiative hazard waste, catastrofic Chernobyl like disasters …and most recent Fukushima Dai-ichi

- Alternative clean energy:
  - solar, not suitable for large urban or industrial center, continuity, accumulation … waste.
  - Wind, not suitable for large urban or industrial center, continuity, accumulation …
  - biofuel (soil erosion, deforestation, desertification, food price …

- Fission (important role , prominent in France) ⟹ but … already mentioned.

- **Fusion: a global approach to a global problem.**
- **<u>THE HOLY GRAAL FOR PRIMARY ENERGY RESOURCES</u>: it requires international collaboration, investments and efforts: ITER …**

Fusion Cross-Section: sorted by kinetic energy

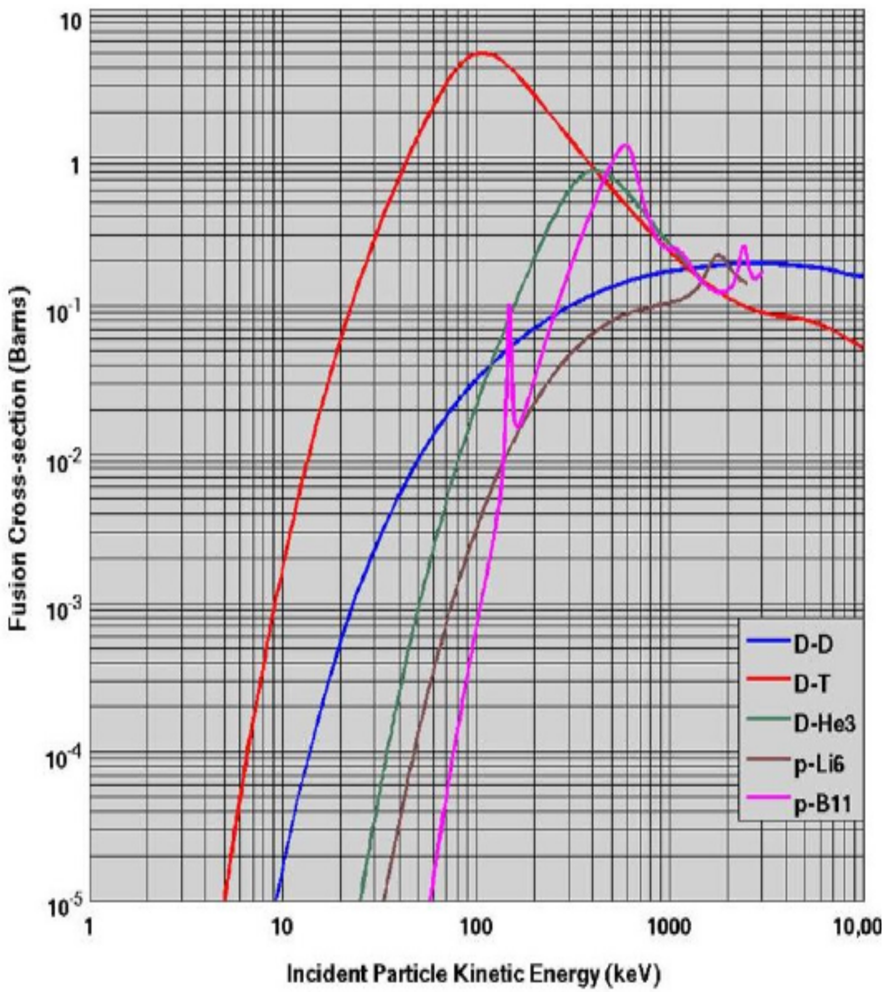


FIG. 1.11. Fusion cross-sections of various fusion reactions as a function of kinetic energy of an incident D or p on a stationary target. The data for the D-D, D-T, D-He^3 and p-^{6}Li curves are taken from the ENDF B-VII database [1.50] for incident deuterium/proton, while that for p-^{11}B is taken from Ref. [1.51]. The curve for D-D represents a sum over the cross-sections of the reaction branches.

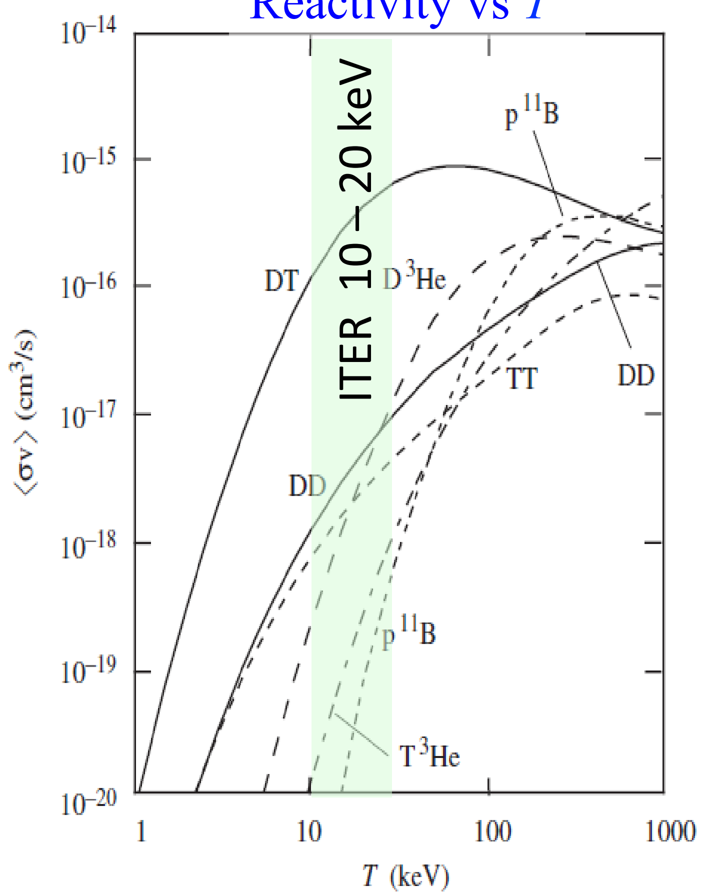
1. D + T → ^{4}He (3.5 MeV) + n (14.1 MeV) — 1st gen
2. D + D → T (1.01 MeV) + p (3.02 MeV) (50%) — 2nd gen
   → ^{3}He (0.82 MeV) + n (2.45 MeV) (50%)
3. D + ^{3}He → ^{4}He (3.6 MeV) + p (14.7 MeV) — 3rd gen
4. T + T → ^{4}He + 2 n + 11.3 MeV
5. ^{3}He + ^{3}He → ^{4}He + 2 p
6. ^{3}He + T → ^{4}He + p + n + 12.1 MeV (51%)
   → ^{4}He (4.8 MeV) + D (9.5 MeV) (43%)
   → ^{4}He (0.5 MeV) + n (1.9 MeV) + p (11.9 MeV) (6%)
7. D + ^{6}Li → 2 ^{4}He + 22.4 MeV
8. p + ^{6}Li → ^{4}He (1.7 MeV) + ^{3}He (2.3 MeV)
9. ^{3}He + ^{6}Li → 2 ^{4}He + p + 16.9 MeV
10. p + ^{11}B → 3 ^{4}He + 8.7 MeV

D-D to start fusion, T produced by n on blanket (containing Litium)
^{6}Li + slow n -> T + 4He + 4.8 MeV (exoE)
^{7}Li + fast n -> T + 4He – 2.5 MeV + n' slow (endoE)

Fusion of polarized fuel: advantages

The three reaction generations are sorted according to relative energy (temperature) required for fusion.

Reactivity vs T



Energy production:

1. Generation: D + T → ^{4}He + n

Polarized fuel

1.a) Increase of total cross section

1.b) differential cross section: angular distrib. $f(\theta)$ therefore better control

2. Generation: D + D → T + p **or** ^{3}He + n

Fuel available (30 g m^{-3} in ocean water)

2.a) Increase ? of total cross section

2.b) Like previous one ? , but still missing data for a complete description.

2.c) Possibility to suppress the reaction (QSF quintet suppression factor)

3. Generation: ^{3}He + D → ^{4}He + p

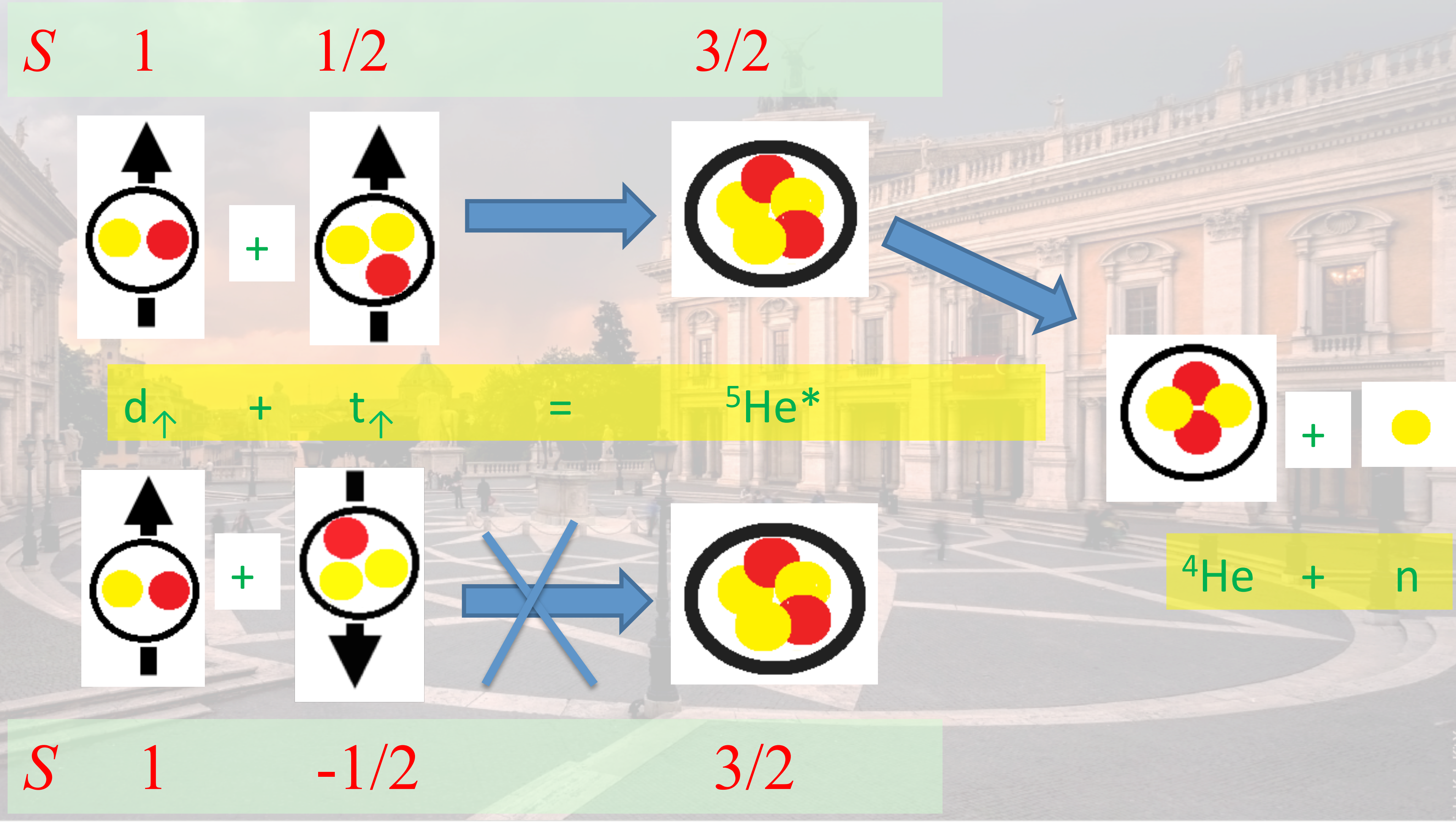
3.a) and 3.b) like 1.a) and 1.b)

3.c) Possibility of Neutron lean reactor if D+D → ^{3}He + n suppressed

The D + D research tokamaks (ITER D + T!).

Fusion Reaction : looking to the spin (S)

$d_{\uparrow}$ ($t_{\uparrow}$, n) ^{4}He two possible spin channels



Fusion with polarized fuel: tested on ^{3}He + d

Can the total cross section of the fusion reactions be increased by using polarized particles ?

$$^3\vec{\mathrm{He}} + \vec{\mathrm{d}} \Rightarrow {}^4\mathrm{He} + \mathrm{p}$$

Factor: ~1.5 at 430 keV

[Ch. Leemann et al., Helv. Phys. Acta **44**, 141 (1971)]

$$\vec{\mathrm{t}} + \vec{\mathrm{d}} \Rightarrow {}^4\mathrm{He} + \mathrm{n}$$

Factor: ~1.5 at 107 keV

Reactions through the spin channel

$J^\pi = 3/2^+$ / S-wave dominated (~96%)

- H. Paetz gen. Schieck *Nuclear physics with polarized particles* (Springer Verlag, Berlin, 2012)
- H. Paetz gen. Schieck, Eur. Phys. J. A **44**, (2010) 321
  Few-Body Syst. **54** (2013) 2159

Enhancement factor 1.5 (simple deduction)

Unpolarized cross section = weighted sum of all channel spin *s*

$$\sigma_{unpol} = \frac{\sum_s (2s+1)\sigma_s}{\sum_s (2s+1)} \qquad \sigma_{unpol} = \frac{2\sigma_{1/2} + 4\sigma_{3/2}}{6} = \frac{1}{3}\sigma_{1/2} + \frac{2}{3}\sigma_{3/2}$$

For both reactions channel spins can be 3/2 and 1/2.

From experiments: both reactions proceed via the $J^\pi = 3/2^+$ ($^5He^*$ and $^5Li^*$).

At low energy the incoming *l* =0 , S-wave dominate:

Only the 3/2 contributes to the σ_{unpol},

if the incoming particles are both polarized:

$$gain = \frac{\sigma_{pol}}{\sigma_{unpol}} = \frac{\sigma_{3/2}}{2/3\sigma_{3/2}} = 1.5$$

Cross section as function of polarization degree *P*

$$\sigma_{pol} = \left[f\left(1+\frac{1}{2}P_z^D P_z^T\right) + (1\text{-}f)\left(1-P_z^D P_z^T\right)\right]\sigma_{unpol}$$

In purely S-wave (*f* =1)

and in case of completely vector polarized D (P_z^D= 1,) and T(P_z^T= 1)

$$\sigma_{pol} = \left(1+\frac{1}{2}P_z^D P_z^T\right)\sigma_{unpol}$$

$$\sigma_{pol} = 1.5\sigma_{unpol}$$

This is to clarify the ***importance*** *of the* ***polarization****.*
when we talk of 1.5 enhancement in cross section,
we're talking about ***pure S-wave interaction*** *and*
both fusing particle populations ***fully polarized****.*

This pushes our efforts to as higher as possible polarization of the fuel.

◎ R.M. Kulsrud *et al.* Nucl. Phys. 26 (1986) 1443-1462

◎ H. Hasuyama *et al.* Helv. Phys. Acta 59 (1986) 723-727

Angular distribution of reaction products

In purely S-wave approx f =1, B along z, (θ) respect to B(z)

$$\left.\frac{d\sigma(\theta)}{d\Omega}\right|_{pol} = \left(1 + \frac{1}{2} P^D_{zz} A_{zz} + \frac{3}{2} P^D_z P^T_z C_{zz}\right) \left.\frac{d\sigma(\theta)}{d\Omega}\right|_{unpol}$$

- A_{zz} *tensor* analysing power A_{zz}= - [3 ($\cos^2$ (θ) -1]/2
- C_{zz} spin correlation coefficient C_{zz}= - 3 [$\cos^2$ (θ) -2]/2

In the d t reaction with d and t polarized parallel to B

$$\sigma_{pol} = 1.5\sigma_{unpol}$$

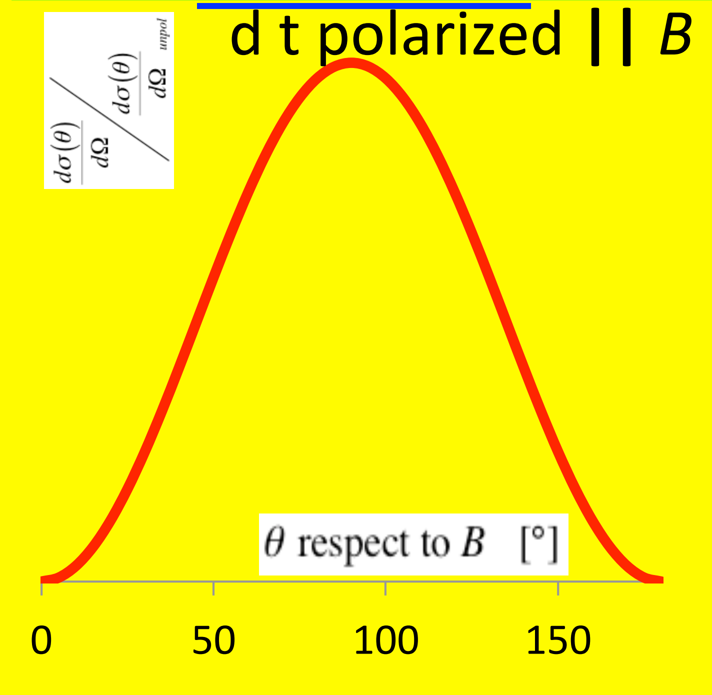
$$\frac{d\sigma(\theta)}{d\Omega} = \frac{9}{4}\sin^2\theta \left.\frac{d\sigma(\theta)}{d\Omega}\right|_{unpol}$$

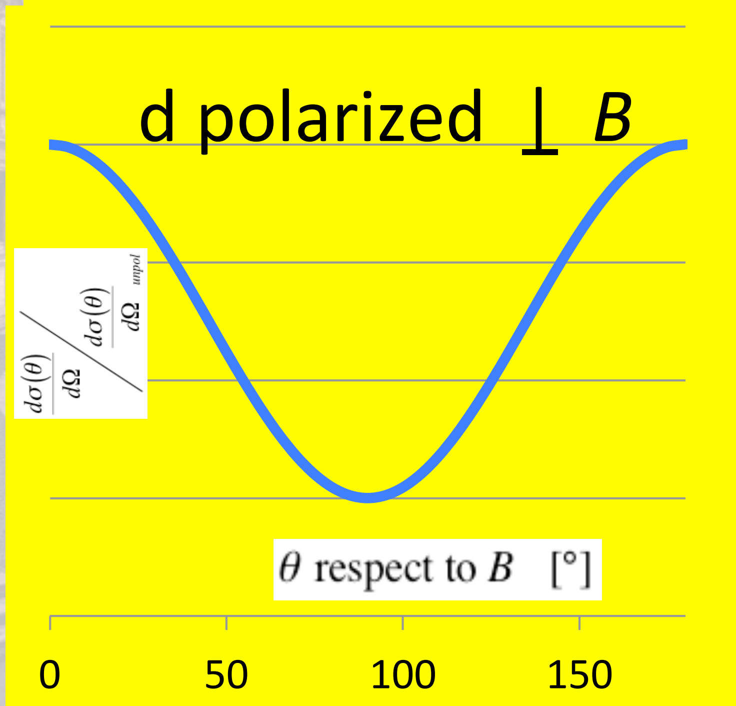
In the case of only d polarized perpendicular to B

$$\sigma_{pol} = \sigma_{unpol}$$

$$\left.\frac{d\sigma(\theta)}{d\Omega}\right|_{pol} = \frac{1}{2}(1 + 3\cos^2\theta) \left.\frac{d\sigma(\theta)}{d\Omega}\right|_{unpol}$$

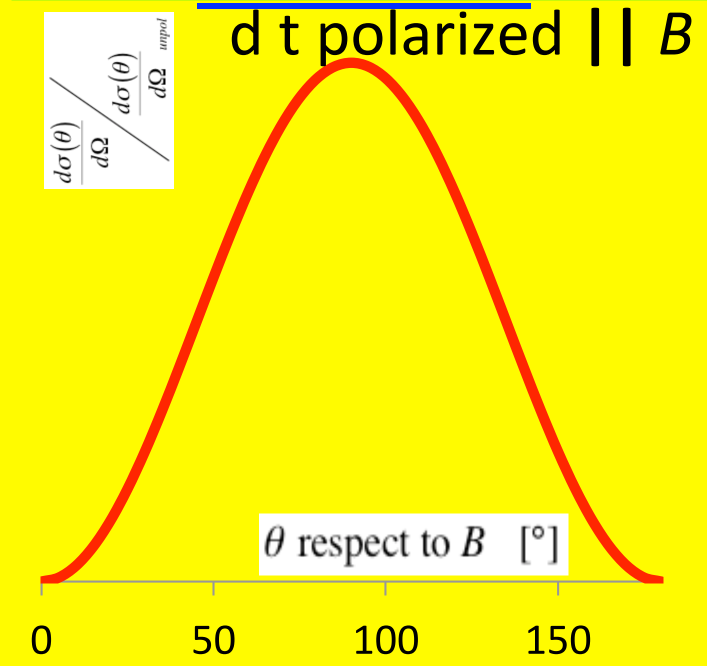
Calculation



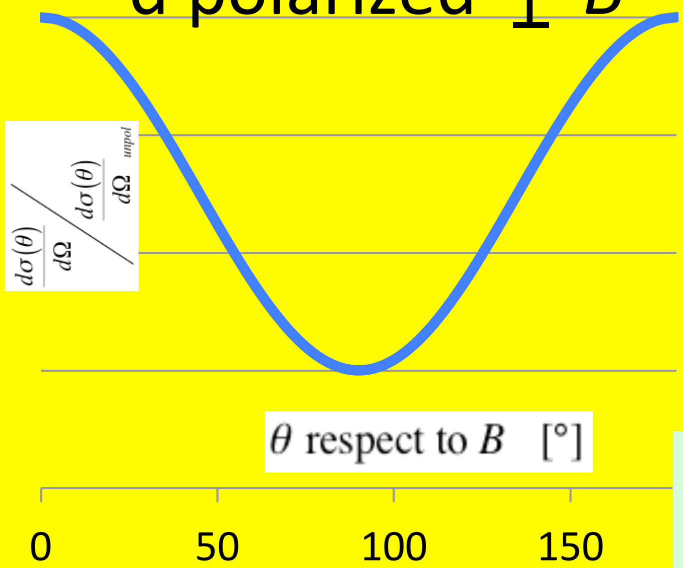


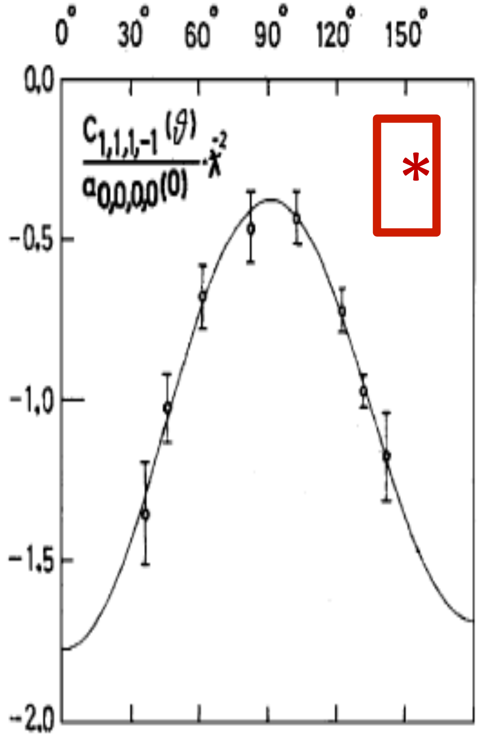
Calculation

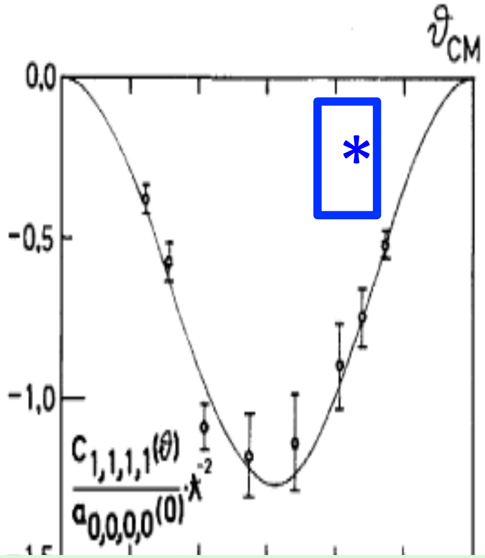
d t polarized || B



d polarized ⊥ B







Experiments

* D and T spin || to the confinement field: α and n emitted as $\sin^2 \theta$ respect to B

* D spin ⊥ to the confinement field and T unpolarized: no influence on cross section, but the reaction products follow $(1+3\cos^2 \theta)$.

Confirmed on mirror reaction $^3He(d,p)^4He$
[Ch. Leeman et al Helv. Phys. Acta **44** (1971) 141]

Fusion with polarized fuel is very promising

- R.M. Kulsrud *et al.* Phys. Rev. Lett. **49** (1982) 1248 **polarized fusion reactor plasmas**.
- E. Bittoni *et al.* Nucl. Fus. **23** (1983) 830, perpendicular spin: reduction of **factor two** on **alpha loading on the wall**.
- B. Coppi Phys. Scripta T2B (1982) 590 address to **neutronless fusion** reacting plasmas, using also **polarized** fuel.
- M.R. More Phys. Rev. Lett. **51** (1983) 396 study for **ICF**.
- B.J. Micklich *et al.* Nucl. Techn./Fus **5** (1984) 162: **relaxed fusion condition** $n\tau_E$ and T_i for ignition and breakeven, more *20% ~ 30%* of **neutron flux localized** in the inboard firt wall (D pol perp to *B*)
- D.A. Noever Fus. Tech. **27** (1995) 86: simple mirror fusion reactors with **polarized fuel,** $Q = P_{fusion} / P_{input}$ =1.63: **new design optimization**.

Still open questions on 1st generation

- Tritium is radioactive T $\rightarrow$ ^{3}He + e$^-$ + anti-ν_e , ($t_{1/2}$=12.3 y) volatile, diffuse in metal, bond in water: not confortable for research investigation.
- We provide **high polarization (0.90) in atomic beam 10^{16} atom/ sec, confined in** special surface for continuous refilling (open tube). Is it possible to combine **polarized molecules** and **store** them?
- How **polarization** behaves in **magnetic fields** ? R. Gatto in www.fe.infn.it/polfusion
- How **polarization** matches existing (and future) projects? F. Bombarda in www.fe.infn.it/polfusion
- **Polarization** can **survive** in plasma? S. Bartalacci in www.fe.infn.it/polfusion

For investigations we follow confortable gas H, D, ^{3}He, or solid target too (HD) - A. D'Angelo - similar spin configuration (DT).

PolFusion project: goals for 1st generation

- Combine in **molecules** polarized atoms, preserving **nuclear polarization**.

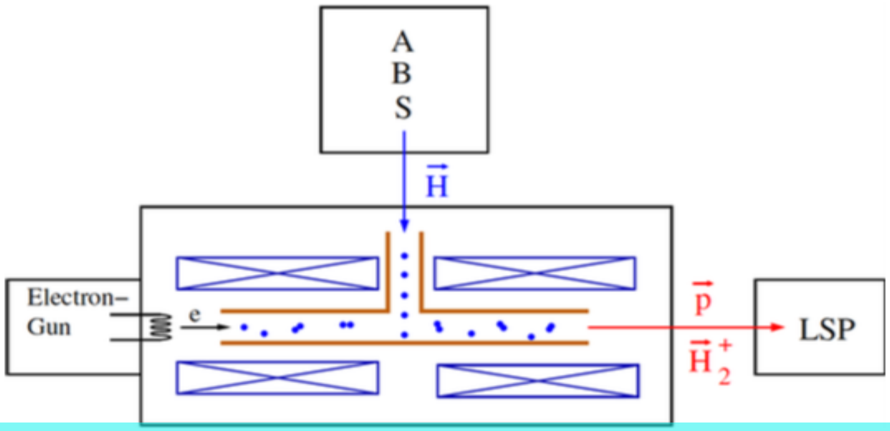
- Follow **laser acceleration** for ion **polarized fuel** production.

This is our challenges for 1st generation fusion reaction, but … working with D it comes out also possible investigation on 2nd and 3rd generation fusion reaction (D + D)

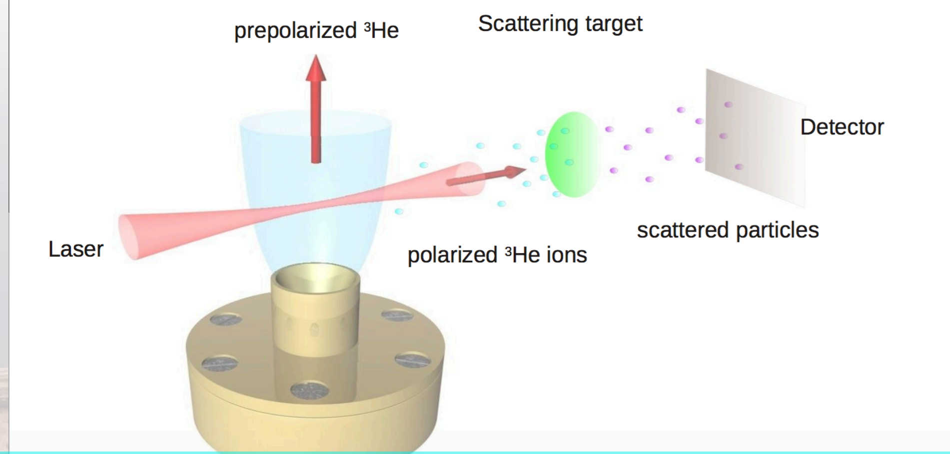
- **D + D** is more diffused fuel (30 g m^{-3} in sea water), and we can test it already in existing research tokamak.

- An more … on D+D reaction, also in order to have the chance to “address” a **neutron** free or **lean** reactor

Goals of PolFusion: for 1st and ... following gen.)



◎ R. Engels *et al.* Phys. Rev. Lett. **115** (2015) 113007-1/5

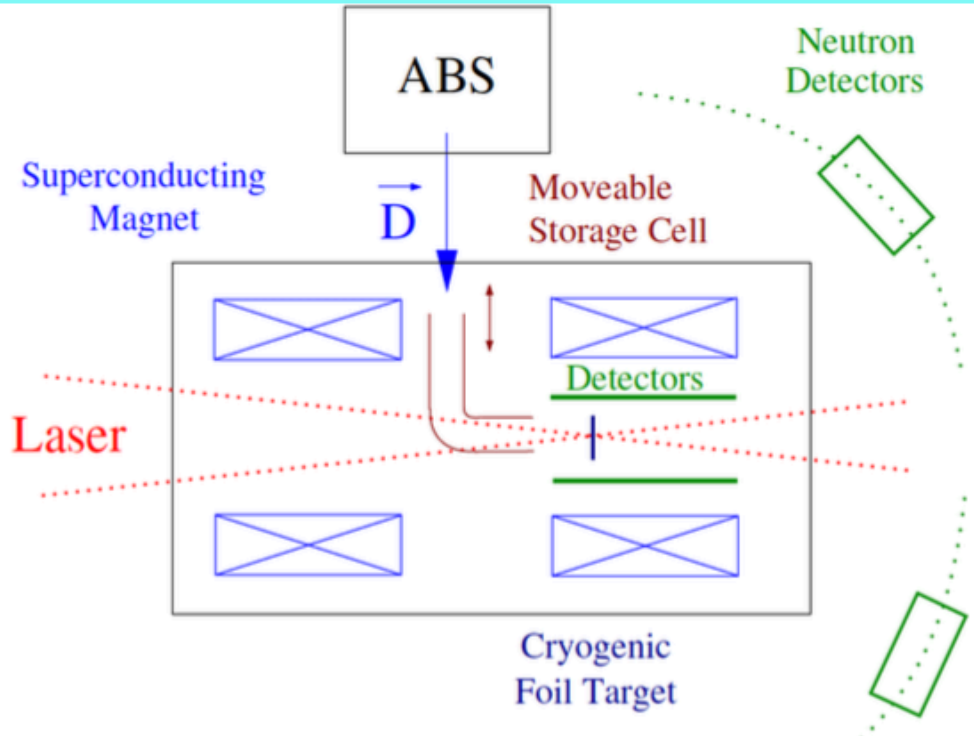


◎ M. Büscher in www.fe.infn.it/polfusion

Finalize the set-up of polarized molecules for deuterium production.

Measurements of polarized beam from laser acceleration.

We'll combine them freezing polarized molecules and by laser acceleration producing polarized ion.



Working with D gives us the chance to investigate

more

for

2^{nd} and 3^{rd} generation reactions

Ans solve still missing data for the understangin of 4N systems

2nd

d + d → t + p 50% (no n)
→ ^{3}He + n 50%(*)

Fusing d + d, then d + t can fuses (n)

^{3}He does not contribute at the ignition energy of d-d

The total cross section d + d in respect to the incoming polarization of the fusing particles:

$$\sigma_{tot} = \frac{1}{9}\left(2\underbrace{\sigma_{1,1}}_{\text{Quintet}} + 4\underbrace{\sigma_{1,0}}_{\text{Triplet}} + \underbrace{\sigma_{0,0}}_{\text{Singlet}} + 2\underbrace{\sigma_{1,-1}}_{\text{Singlet}}\right)$$

Hjgher energy for fusion involves P-, D-wave, togheter with S-wave and their interferences

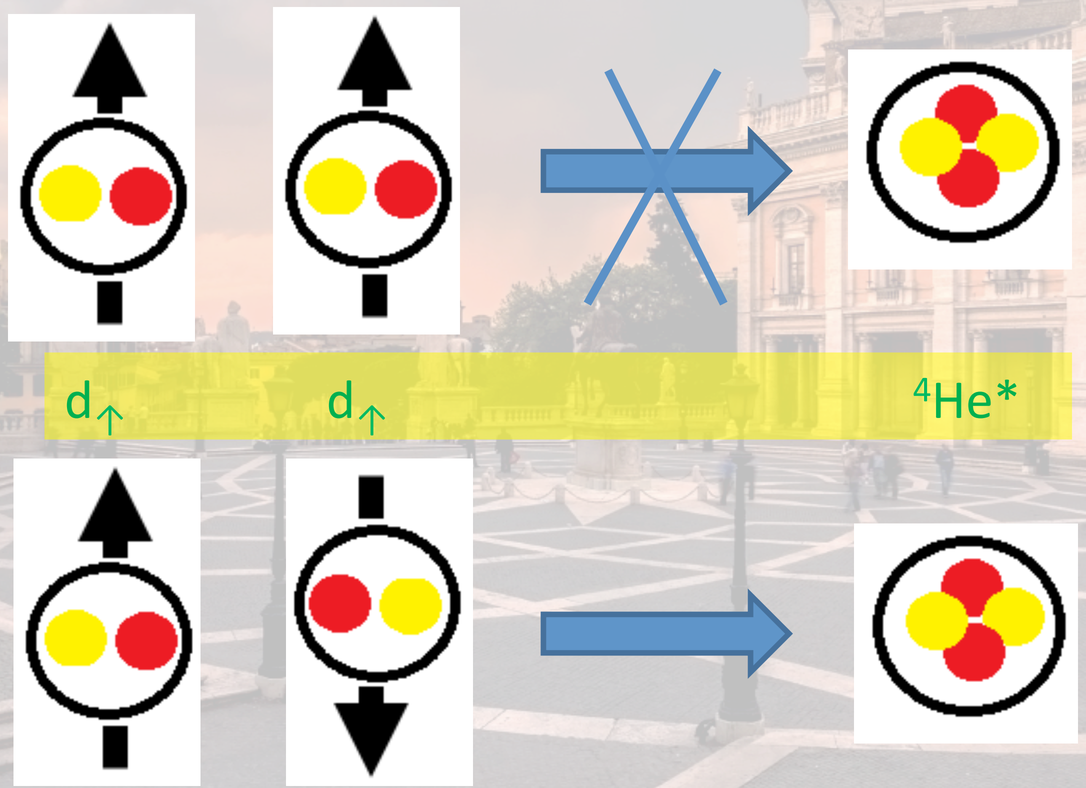
$d_{\uparrow} + d_{\uparrow}$ spin dependent cross section (data set very poor), and still worse at lower energy (electron screening ?)

Neutron lean fusion: QSF (Quintet Suppression Factor)

Spin alignements allows to enhance or suppress reaction channels?
Ad'yasevich 2.5 -3

$D_{\uparrow}$ ($d_{\uparrow}$ p) T and $D_{\uparrow}$ ($d_{\uparrow}$ n) ^3He suppressed
by choosing deuteron spin parallel each others

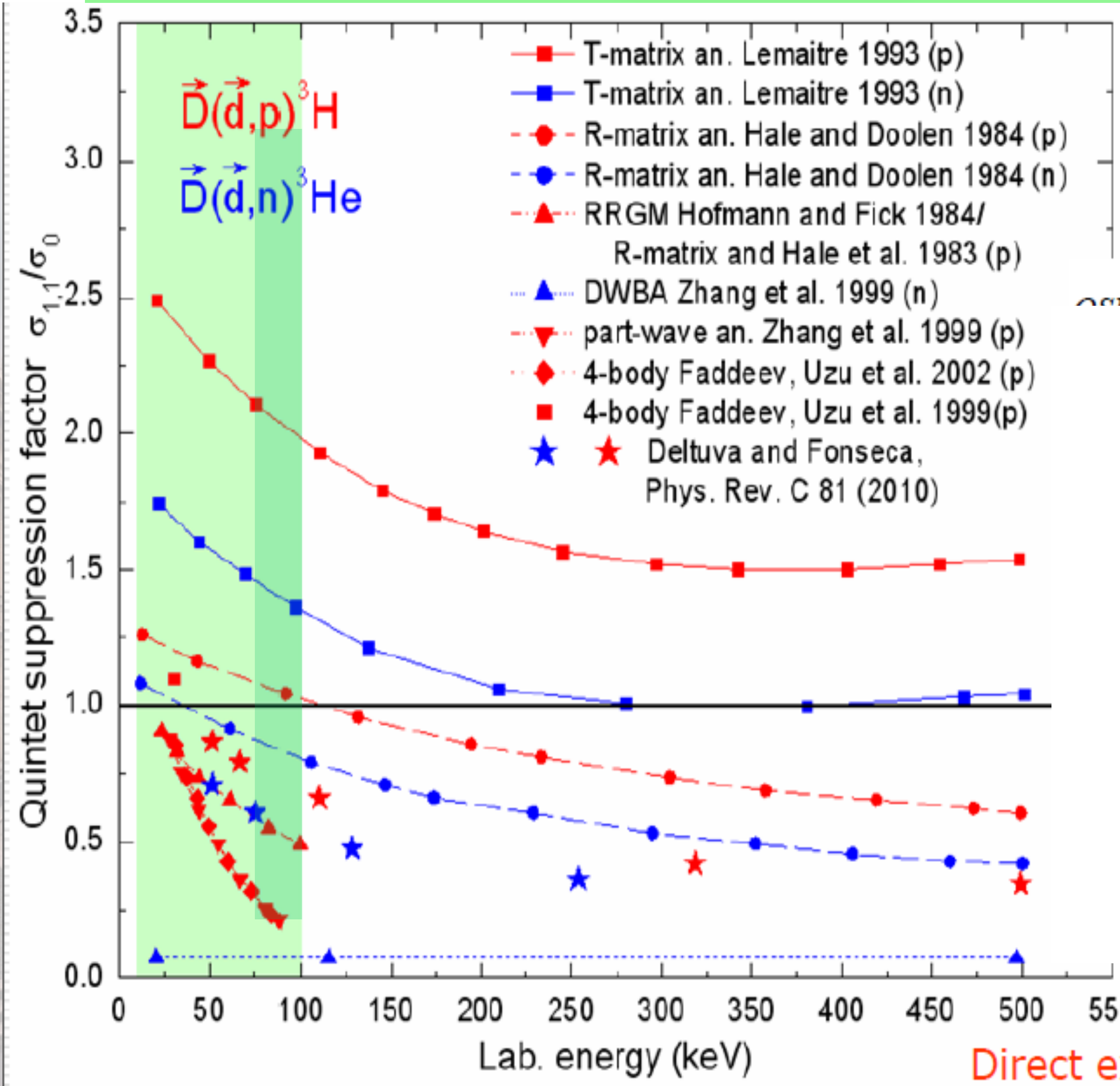
S 1 1 0 $^5S_2$ Quintet State Suppressed



$$\frac{\sigma_{pol}}{\sigma_{unpol}} = \frac{\sigma_{singlet}}{3/9\,\sigma_{singlet}} = 3$$

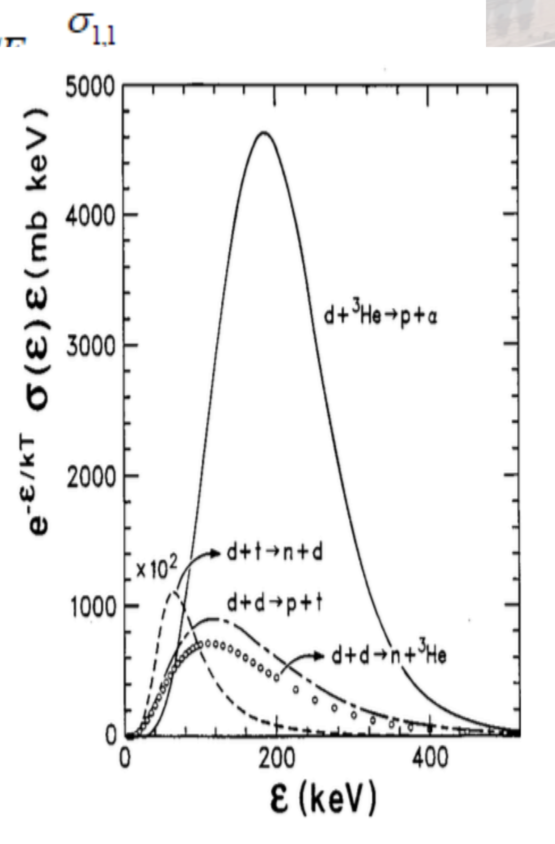
S 1 -1 0 $^1S_0$ Singlet state allowed

QSF: exp. challenge for previsions



Deltuva in
Nuclear fusion with
polarized nucleons
Trento 14-15 Nov 2013

$\sigma_{1,1}$



Direct experiment required!

3^{rd}

Neutron lean fusion

$d + {}^3He \rightarrow {}^4He + p$?

Can we have neutron free reactor?

The spin configuration is 1 + ½, like the t + d, and was confirmed experimentally already in the 1971

If we suppress or reduce D-D fusion, we could have neutron free or lean reactors

We said "lean", because we'll still have n from D + T, T produced in D + D reaction.

To answer to the D D polarized fusion we need to know the cross section of the whole set of orientation of the spin T produced in D + D reaction.

D + D cross section: analysing powers *A* and spin correlation coeff. *C*

$$
\begin{aligned}
\sigma(\Theta,\Phi) = \sigma_0(\Theta)\,\{1 \;&+\; \frac{3}{2}\left[A_y^{(b)}(\Theta)p_y + A_y^{(t)}q_y\right] + \frac{1}{2}\left[A_{zz}^{(b)}(\Theta)p_{zz} + A_{zz}^{(t)}(\Theta)q_{zz}\right] \\
&+\; \frac{1}{6}\left[A_{xx-yy}^{(b)}(\Theta)p_{xx-yy} + A_{xx-yy}^{(t)}(\Theta)q_{xx-yy}\right] \\
&+\; \frac{2}{3}\left[A_{xz}^{(b)}(\Theta)p_{xz} + A_{xz}^{(t)}(\Theta)q_{xz}\right] \\
&+\; \frac{9}{4}\left[C_{y,y}(\Theta)p_y q_y + C_{x,x}(\Theta)p_x q_x + C_{x,z}(\Theta)p_x q_z \right.\\
&\qquad \left. + C_{z,x}(\Theta)p_z q_x + C_{z,z}(\Theta)p_z q_z\right] \\
&+\; \frac{3}{4}\left[C_{y,zz}(\Theta)p_y q_{zz} + C_{zz,y}(\Theta)p_{zz} q_y\right] \\
&+\; C_{y,xz}(\Theta)p_y q_{xz} + C_{xz,y}(\Theta)p_{xz} q_y + C_{x,yz}(\Theta)p_x q_{yz} \\
&+\; C_{yz,x}(\Theta)p_{yz} q_x + C_{z,yz}(\Theta)p_z q_{yz} + C_{yz,z}(\Theta)p_{yz} q_z \\
&+\; \frac{1}{4}\left[C_{y,xx-yy}(\Theta)p_y q_{xx-yy} + C_{xx-yy,y}(\Theta)p_{xx-yy} q_y \right.\\
&\qquad \left. + C_{zz,zz}(\Theta)p_{zz} q_{zz}\right] \\
&+\; \frac{1}{3}\left[C_{zz,xz}(\Theta)p_{zz} q_{xz} + C_{xz,zz}(\Theta)p_{xz} q_{zz}\right] \\
&+\; \frac{1}{12}\left[C_{zz,xx-yy}(\Theta)p_{zz} q_{xx-yy} + C_{xx-yy,zz}(\Theta)p_{xx-yy} q_{zz}\right] \\
&+\; \frac{4}{9}\left[C_{xz,xz}(\Theta)p_{xz} q_{xz} + C_{yz,yz}(\Theta)p_{yz} q_{yz}\right] \\
&+\; \frac{8}{9}\left[C_{xy,yz}(\Theta)p_{xy} q_{yz} + C_{yz,xy}(\Theta)p_{yz} q_{xy}\right] \\
&+\; \frac{16}{9} C_{xy,xy}(\Theta)p_{xy} q_{xy} \\
&+\; \frac{1}{9}\left[C_{xz,xx-yy}(\Theta)p_{xz} q_{xx-yy} + C_{xx-yy,xz}(\Theta)p_{xx-yy} q_{xz}\right] \\
&+\; \frac{1}{36} C_{xx-yy,xx-yy}(\Theta)p_{xx-yy} q_{xx-yy} \\
&+\; \frac{1}{2}\left[C_{x,xy}(\Theta)p_x q_{xy} + C_{xy,x}(\Theta)p_{xy} q_x + C_{z,xy}(\Theta)p_z q_{xy} \right.\\
&\qquad \left. + C_{xy,z}(\Theta)p_{xy} q_z\right]\,\}
\end{aligned}
$$

Spins of both deuterons aligned: only $p_z(q_z)$ and $p_{zz}(q_{zz}) \neq 0$

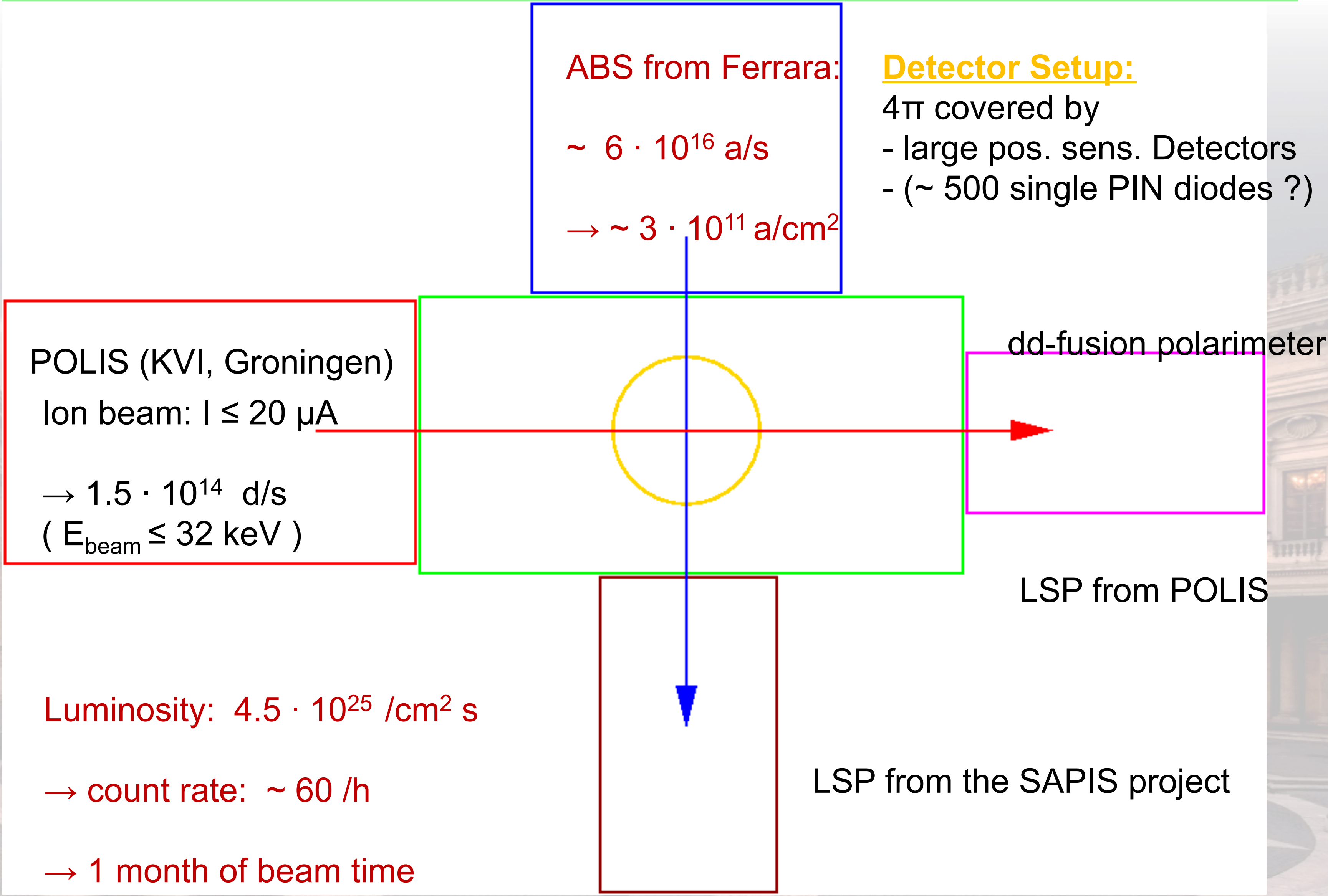
$$
\begin{aligned}
\sigma(\Theta,\Phi) = \sigma_0(\Theta)\,\{1 \;&+\; \frac{3}{2}\left[A_{zz}^{(b)}(\Theta)p_{zz} + A_{zz}^{(t)}(\Theta)q_{zz}\right] \\
&+\; \frac{9}{4} C_{z,z}(\Theta)p_z q_z + \frac{1}{4} C_{zz,zz}(\Theta)p_{zz} q_{zz}\,\}
\end{aligned}
$$

Only beam is polarized:
$(p_{i,j} \neq 0,\ q_{i,j} = 0)$

$$
\begin{aligned}
\sigma(\Theta,\Phi) = \sigma_0(\Theta) \cdot \{1 &+ 3/2\, A_y(\Theta)\, p_y \\
&+ 1/2\, A_{xz}(\Theta)\, p_{xz} \\
&+ 1/6\, A_{xx-yy}(\Theta)\, p_{xx-zz} \\
&+ 2/3\, A_{zz}(\Theta)\, p_{zz}\,\}
\end{aligned}
$$

H. Paetz gen. Schieck,
Eur. Phys. J. A **44**, (2010) 321

The D D setup: A. Vassilyev in www.fe.infn.it



Detector Setup:

4π covered by
- large pos. sens. Detectors
- (~ 500 single PIN diodes ?)

Luminosity: 4.5 · 10^{25} /cm^2 s

→ count rate: ~ 60 /h

→ 1 month of beam time

Partial measurements, not in the whole interesting energy range and with lower luminosity available (Deltuva, Schieck, Zhang,Tagishi ...

Conclusions …

PolFusion - one day discussion Meeting

(Round-Table on perspectives and milestones on nuclear fusion with polarized fuels)

July 23RD, 2015
IUSS, Via Scienze 41b, 44121 Ferrara (Italy)

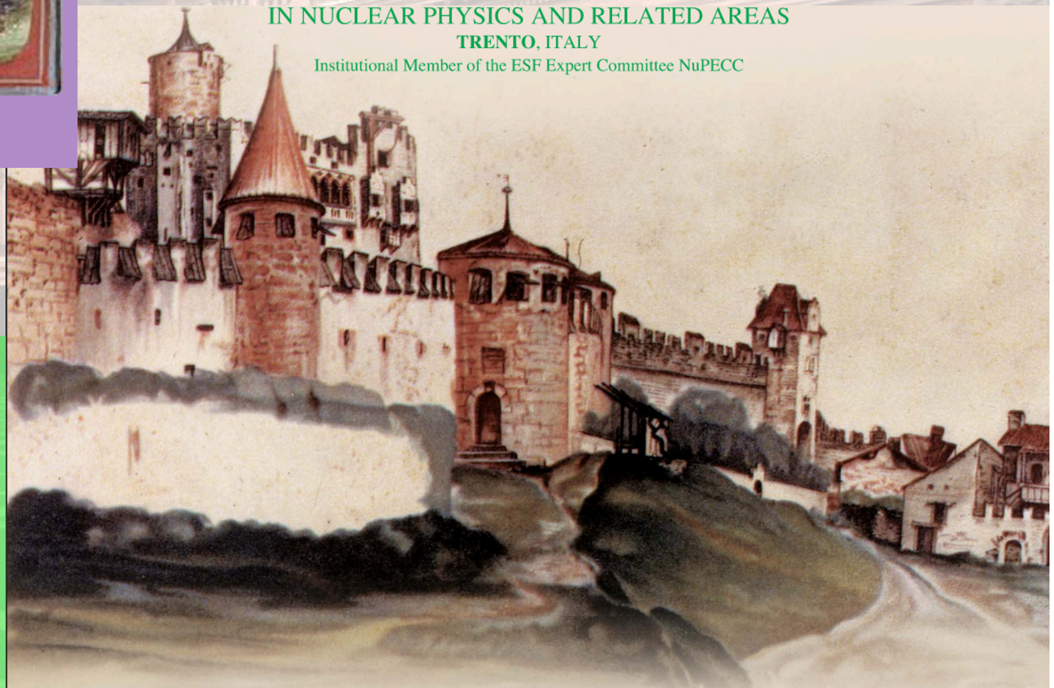
Spin game fresco (Game hall) in the Estense Castle of Ferrara
Sebastiano Filippi (Bastianino) XVI sec.

www.fe.infn.it/polfusion

More information:
On presentations of meetings

http://www.ectstar.eu/node/379

IN NUCLEAR PHYSICS AND RELATED AREAS
TRENTO, ITALY
Institutional Member of the ESF Expert Committee NuPECC



Castello di Trento (“Trint”). watercolour, 19.8 x 27.7, painted by A. Dürer on his way back from Venice (1495) British Museum, London.

Nuclear Fusion with Polarized Nucleons (Collaboration Meeting)
Trento, November 14-15, 2013

Hoping to succeed in polarized fuel …. for testing polarized fusion.