Spin Polarized Fusion (SPF) Workshop

December 9-10, 2024

Advanced Research Projects Agency • Energy

ARPA-E Headquarters
950 L'Enfant Plaza SW
Washington, DC

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WIP Frascati 3/2/2025

https://arpa-e.energy.gov/

Who We Are

The disruption wing of the Department of Energy (DOE). First. Fast. Ambitious. We're an agency of energy scientists, technologists, entrepreneurs, engineers, and industry visionaries who dare to disrupt the status quo.

What We Do

American-made energy for all. Our projects aim to radically improve our standing in the global energy landscape while bringing energy manufacturing back home to support local communities. We focus on diverse technologies that can be meaningfully advanced with a small amount of funding and active project management over a defined period of time. Our streamlined awards process enables us to act quickly to drive disruption across the entire energy portfolio.

How We Do It

Technical Oversight. Speed. Impact. Rigorous program design, milestone definition, and active program management enables technical advancement. To ensure a steady stream of disruptive thinking, eliminate bureaucratic slowdowns, and maintain a bias for action, our Program Directors serve for limited terms.

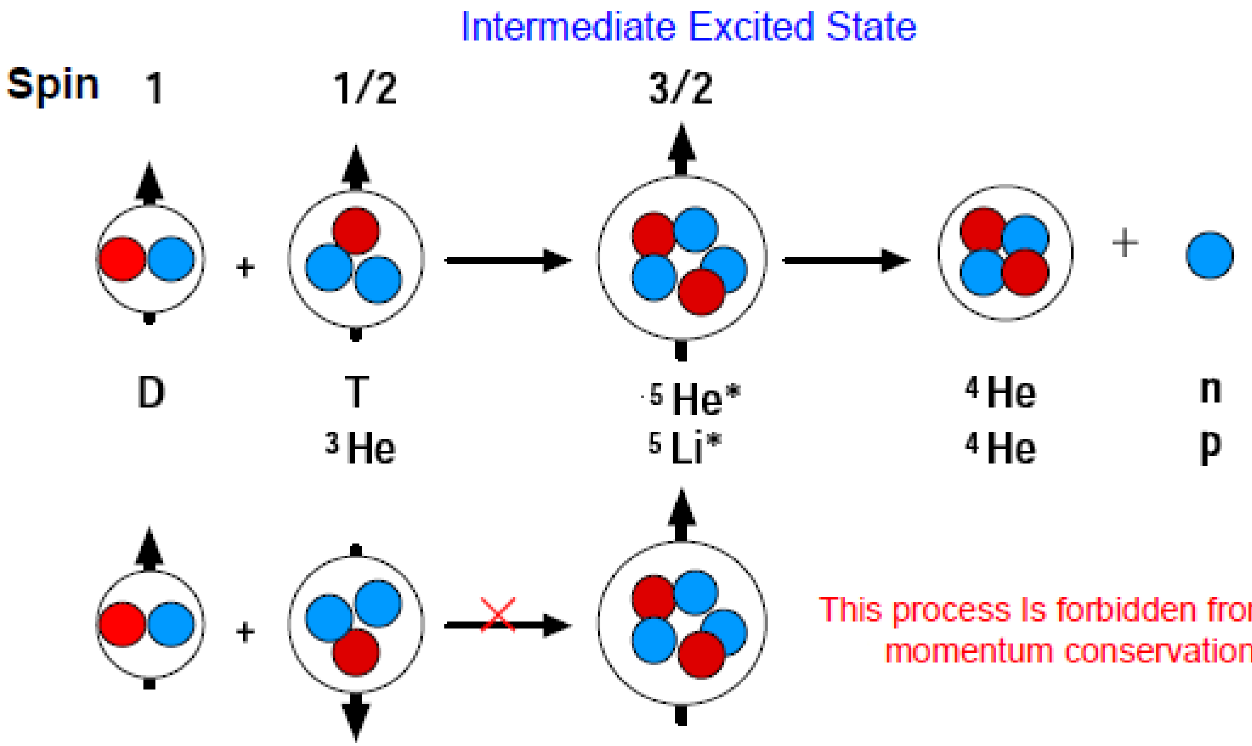
Merit in Fusion Cross Section

By angular momentum Conservation

In the case of D-T (D-^{3}He)

Enhancement : $\sigma^{\uparrow\uparrow} = 1.5 \cdot \sigma_0$

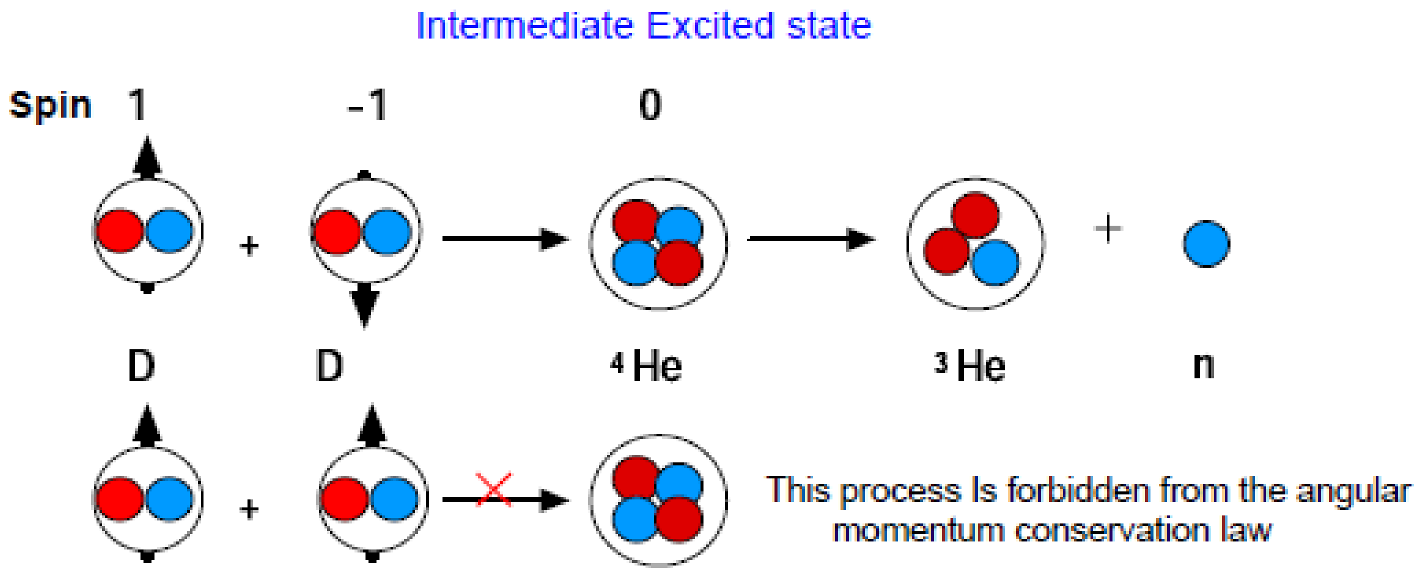
(σ_0 : Cross section for unpol. Beam and Target)



This process Is forbidden from the angular momentum conservation law

From: “Basic studies on polarized D-D-fusion”,
Naoaki Horikawa, College of Engineering, Chubu University
International Symposium on Polarized Target and its Application
Tsukioka-Hotel, Kaminoyama-Onsen, Yamagata (2008)

In the case of D-D : $\sigma^{\uparrow\downarrow} \sim (2-3)\,\sigma_0$



For D-D estimates of actual cross sections still uncertain due to the large number of terms

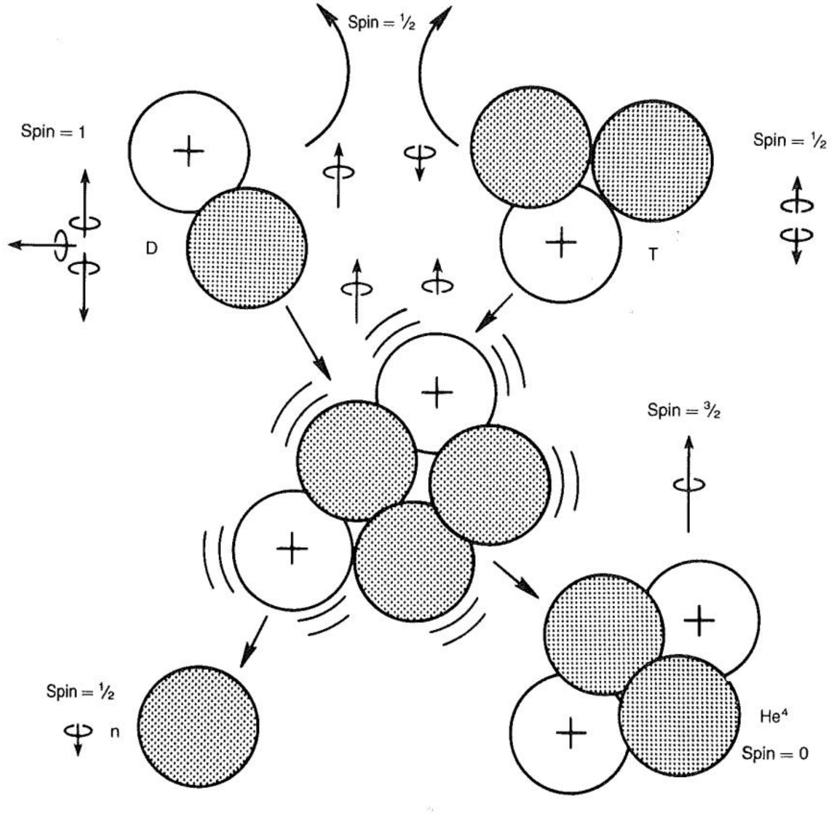
	H	D	T	^{3}He
I	0.5	1.	0.5	0.5
f_{ci} MHz/T	15.20	7.60	5.05	10.14
μ_0 MHz/T	42.57	6.53	45.43	32.44
ΔE_m 10^{-7} eV/T	1.76	0.27	1.88	1.34
μ_0/f_{ci}	2.8	0.86	9.	3.2

Fusion with polarized atoms (an idea of the fab '80)[1]

1. In theory, polarized D-T, D-D, or D-^{3}He plasmas should have higher fusion yields by a factor 1.5-2
2. Fusion products, in particular neutrons, would be emitted in preferential directions
3. In D-D reactions, the D(D,n)^{3}He can be totally suppressed

- If polarized atoms are injected in a fusion device, all the de-polarization mechanisms (collisions, ionization, field gradients, etc.) were estimated to have a time scale longer than the ion life-time.

[1]Kulsrud, Furth, et al., PPPL Report 1912 (1982)



Deuterium–tritium fusion at reactor energies proceeds primarily through an intermediate spin-3/2 resonance of He^5, 107 keV above the sum of the D and T masses. A deuteron–triton collision in a spin-½ state will contribute almost nothing to the fusion cross section. Thus if one could align all D and T spins parallel to the reactor's magnetic field, the fusion cross section would be enhanced by 50%. The emerging energetic alpha and neutron come off with an $\ell = 2$, $\sin^2\theta$ angular distribution that would be particularly useful in mirror machines. Open (shaded) circles are protons (neutrons). Each spin-S state has $2S+1$ possible orientations,

R. M. Kulsrud, H. P. Furth, E.J. Valeo and M. Goldhaber
Physics Today(August, 1982)
PRL49(1982)1248-1251

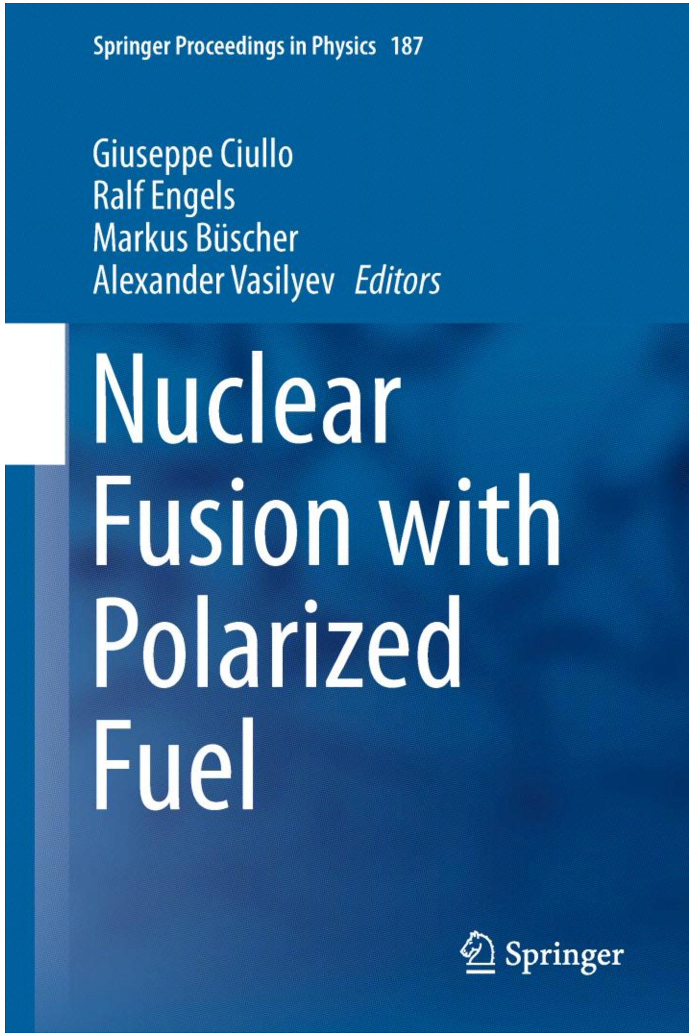
BUT… Coppi *et al.*[2,3]

objected that magnetic field fluctuations in the plasma would quickly de-polarized the ions. Given also the technical difficulty of producing highly polarized beams, the idea was dism

$$\nu_{dep} \simeq 4\times10^{3}\left(\frac{\Omega_D^{k}}{10\Delta\omega}\right)\left|\frac{10\ B_\perp}{B}\right|^{2}\left(\frac{B}{5\times10^{4}\,\text{gauss}}\right)\ s^{-1} \qquad (6)$$

A similar estimate is obtained under the assumption of a broad spectrum by counting the number of the relevant standing waves and by normalizing the fluctuation level one order smaller. These estimates indicate that the rate of spin depolarization can be significantly faster than that of fusion reaction and would lead us to conclude that after thermonuclear burn begins the deuterium spins are rapidly depolarized.

[2]B. Coppi, F. Pegoraro, J. Ramos, *Proceed. 11th EPS Conf. Controll. Fusion and Plasma Phys.* paper D47, p 241, 1983
[3]B. Coppi, S. Cowley, R. Kulsrud, P. Detragiache , F. Pegoraro, Phys. Fluids **29**, 4060 (1986)



PolFusion - one day discussion Meeting
23rd of July 2015 – Ferrara
Contrib. F. Bombarda, A. Cardinali, C. Castaldo

Agenda

MONDAY, DECEMBER 9, 2024

8:00 – 9:00 AM Registration & Networking Breakfast

9:00 – 9:10 AM **Opening Remarks, Workshop Overview and Objectives**
Ahmed Diallo, Program Director, ARPA-E

9:10 – 9:15 AM **Spin Polarized Fusion Activities in DOE Office of Science**
Matthew Lanctot, DOE SC Fusion Energy Sciences (FES)

9:15 – 9:50 AM **Overview of the Spin Polarized Fusion Landscape**
Andrew Sandorfi, University of Virginia

9:50 – 10:10 AM **Status of the Planned DIII-D Experiments and Lifetime Measurement of Spin Polarized D-He3**
Xiangdong Wei, Jefferson Lab

10:10 – 10:35 AM **Polarization Lifetime Measurements in DIII-D and Other Magnetic Fusion Experiments**
Bill Heidbrink, University of California, Irvine

10:35 – 11:00 AM Networking/Discussion Break

11:00 – 11:25 AM **The PREFER (Polarization REsearch for Fusion Experiments and Reactors) Collaboration: Aims, Goals and Present Status**
Giuseppe Ciullo, University of Ferrara

11:25 – 11:50 AM **First Experience with the Production, Storage and Handling of Polarized D2 and HD Molecules**
Ralf Engels, Institut für Kernphysik (IKP) Jülich

- 3 M$ / 2yrs
- Polarize D, ^{3}He --> Inj tok --> diagnose
- Int collaborations not yet in place

Production of Spin Polarized Molecules via IR or Microwave Rotational Excitation of Molecular Beams
Peter Rakitzis, FORTH Institute for Electronic Structure and Laser (IESL)

Networking Lunch

Polarized Beams From Plasma Accelerators and Prospects for Polarized Fusion
Markus Büscher, Forschungszentrum Jülich (FZJ)

Concepts for Spin-Qubit Based Polarisation and Negative Ion Detachment of Hydrogen from Diamond Surfaces
Alastair Stacey, Princeton Plasma Physics Laboratory (PPPL)

Challenges of D-T Spin Polarization for ICF
James Sater, Lawrence Livermore National Laboratory (LLNL)

Break / Transition to Breakouts

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A. Sandorfi (U. VA) - Overview

- Main proponent of experiment on DIII-D as solid polarized pellet expert
- Gain only if both species are polarized. For details see L. Baylor et al, Polarized fusion and potential in situ tests of fuel polarization survival in a tokamak plasma (Nucl. Fusion **63** (2023) 076009) --> over optimistic !
- Ignores depolarization by microinstabilities
- Polarized solid require high B and low T
- Atomic beam (Stern-Gerlach) sources limited to 10^{17} sec^{-1}
- New high flux laser-driven sources may be up to 10^{22} sec^{-1}
- In DIII-D solid LiD cylinders (~3×10^{20} D), ^{3}He, D pellets into (neutronless) H or He plasmas

DIII-D experiment

- Wei (Jefferson Lab) : D-^{3}He, D polarized by Dynamical Nuclear Polarization (LiD), ^{3}He in ICF capsules
- Heidbrink (UCIrvine): polarization lifetimes

--> essentially measure the neutron emission anisotropy at different locations (DIAGNOSTICS?)

- Enhancement of DD cross section calculated (maybe) but not experimentally verified
- Round Table: Estimate depolarization by fluctuations using ITPA tools to figure out instabilities in the precession frequency range (~ICR)

Conceptual design of DIII-D experiments
to diagnose the lifetime of spin polarized fuel
A.V. Garcia, W.W. Heidbrink, and A.M. Sandorfi, Nucl. Fusion **63** (2023) 026030
https://doi.org/10.1088/1741-4326/acaf0d

A research program to measure the lifetime of spin polarized fuel
W.W. Heidbrink et al., Frontiers in Physics 1355212 (2024)

The PREFER collaboration/projects

Giuseppe Ciullo INFN & *University of Ferrara*

on behalf of the

PREFER

Polarization **RE**search for **F**usion **E**xperiments and **R**eactors

COLLABORATION

Group (Responsible)	Institute
R. Engels et al.	IKP - FZJ @ Jülich & GSI- Darmstadt, Germany
M. Büscher et al.	PGI - FZJ @ Jülich ILPP- HH University @ Düsseldorf
G. Ciullo et al.	INFN & University @ Ferrara
T.P. Rakitzis et al.	IESL-FORTH & University @ Crete

Conclusions of PREFER activities

We are still enjoy playing with spin for nuclear fusion, and we are coming closer and closer, hoping to have social, economic and environmental impacts.

Some more information:

Sebastiano Filippi (named Bastianino) "The spin game"
A fresco on the cieling of the Games's Hall – Este Castle – Ferrara
dated after the earthquake of 1570.

ARPA-E Day 2

- Richard Milner (MIT): New Electron-Ion Collider https://www.bnl.gov/eic/ (ex RHIC) in 2034 3$B
- Sofia Quaglioni (LLNL): *ab initio* calculations of SPF

- No measures for DD, (and little for DT or D^3He)
- Screening effect for beam-target reactions: atomic e^- screen the target and enhance σ, also of astrophysical interest
- Calculations seem to point to no enhancement and no suppression of the quintet channel

For DD look at: Paetz gen. Schieck, H. The status of "polarized fusion". *Eur. Phys. J. A* **44**, 321–354 (2010). https://doi.org/10.1140/epja/i2010-10964-4

Conclusions

- Cross sections and plasma modelling a priority for DT
- Screening effects at low temperatures
- In DT, also the outcoming neutron is polarized --> no calculations of impact on the breeding cross sections.
- Economics: 10^{22} sec^{-1}, 0.10 g/s
- Not clear if there is an advantage in PF
- Issues with polarization measurements

My take-aways

- The topic is interesting from the physics point of view, but unlikely to be of practical use;
- The DIII-D experiment is based on unrealistic assumptions (almost nobody from the tokamak world was at the meeting)
- Does not appear to be keen on foreign contributions
- Ignoring ICF-based diagnostics

REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 74, NUMBER 3 MARCH 2003

Evaluation of possible nuclear magnetic resonance diagnostic techniques for tokamak experiments

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