

Overview of the Spin-Polarized-Fusion Landscape

Andrew M. Sandorfi
University of Virginia
Dec 9, 2024

- (1) Historical Perspective
- (2) Potential Gains from Polarization
- (3) Polarized Materials developed for Nuclear/Particle Physics & Medical Imaging
- (4) Depolarization Mechanisms
- (5) Potential for Large-Scale Fueling of a Power Reactor with Polarized Fuel
- (6) The DIII-D Polarization Survival Experiment
- (7) Options for Testing Polarization Survival

Summary

(1)

VOLUME 49, NUMBER 17

PHYSICAL REVIEW LETTERS

25 OCTOBER 1982

MCF :

Fusion Reactor Plasmas with Polarized Nuclei

R. M. Kulsrud, H. P. Furth, and E. J. Valeo

Princeton Plasma Physics Laboratory, Princeton, New Jersey 08544

and

M. Goldhaber

Brookhaven National Laboratory, Upton, New York 11973

(Received 25 May 1982)

*neither speculated how
to make enough fully
polarized fuel,
nor how to get it to
where it had to be*

VOLUME 51, NUMBER 5

PHYSICAL REVIEW LETTERS

1 AUGUST 1983

ICF :

Nuclear Spin-Polarized Fuel in Inertial Fusion

Richard M. More

Lawrence Livermore National Laboratory, Livermore, California 94550

(Received 1 February 1983)

⇔ a flurry of activity in the 1980s: 61 papers, 2 Conferences / Workshops

- then subsequent work all but died out because:

(1) technical challenges in testing polarization survival:

- few options for polarizing hydrogens

- ⇔ only optically-pumped atomic gas beams,
too low intensities for either MCF or ICF

- MCF: only injection option was gas puffing:

- ⇔ difficult to reach the plasma core directly

- ⇔ multiple wall collisions likely to depolarize

- ICF: difficult to prepare an ICF pellet

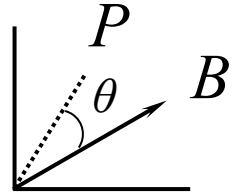
- ⇔ from NP, depolarization rate of polarized gas
~ surface/volume ratio & vessel coatings

(2) large-scale fueling of a power reactor seemed beyond reach

(2) Gains from spin-dependent $^3\text{He}+D \rightarrow \alpha + p$ or $T+D \rightarrow \alpha + n$ reactions

- polar (pitch) angles measured relative to the local magnetic field direction

$$\frac{d\sigma}{d\Omega_{cm}} = \left(\frac{d\sigma}{d\Omega} \right)_0 \left\{ 1 - \frac{1}{2} P_D^V P_{^3\text{He}} + \frac{1}{2} \left[3 P_D^V P_{^3\text{He}} \sin^2 \theta + \frac{1}{2} P_D^T (1 - 3 \cos^2 \theta) \right] \right\}$$



[Sandorfi, D'Angelo, Springer Proc Phys **187** (2016) 115]

[Baylor et al, NF **63** (2023) 076009]

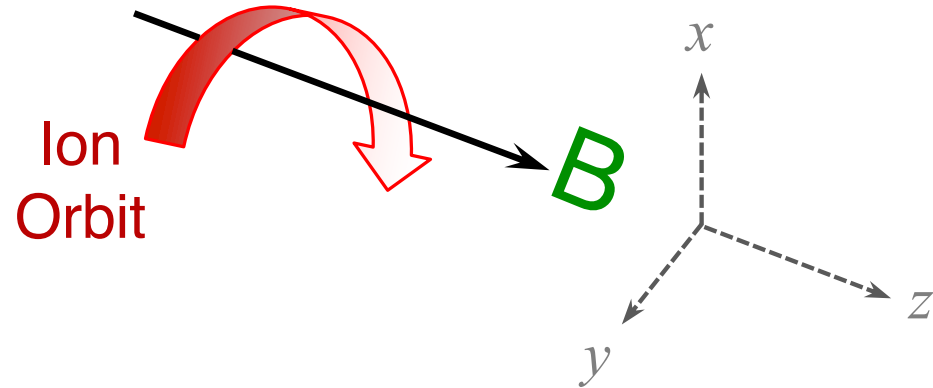
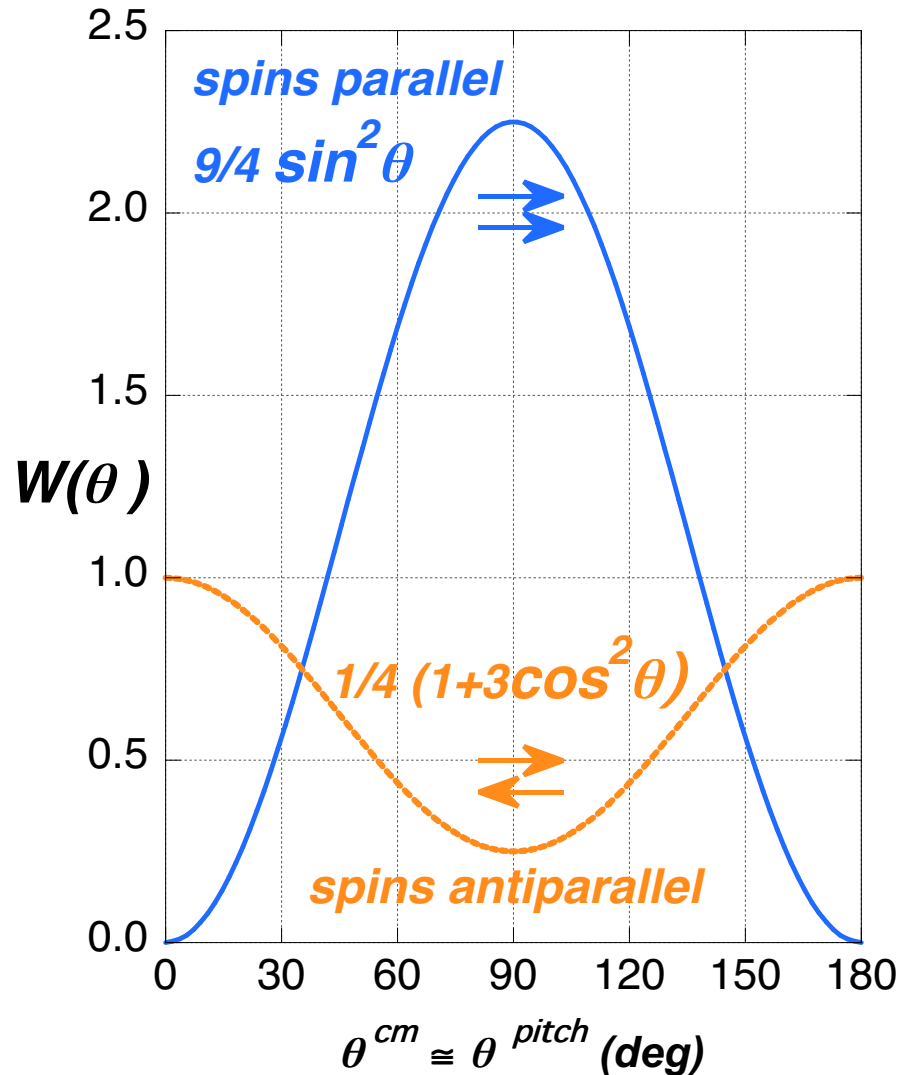
- $P_D^V = n_D^{+1} - n_D^{-1} \in [-1, +1]$
- $P_D^T = n_D^{+1} + n_D^{-1} - 2n_D^0 \in [-2, +1]$
- $P_{^3\text{He}} = n_{^3\text{He}}^{+1/2} - n_{^3\text{He}}^{-1/2} \in [-1, +1]$

- P^T term drops out when integrated over θ
- no net effect unless BOTH species polarized

Assumptions:

- angular-momentum and parity conservation
- reactions dominated by a single compound nuclear state (in ^5Li or ^5He)
 - interference terms contribute $\sim 2\text{-}3\%$ at most [Baylor et al, 2023 Nucl. Fusion **63**, 076009]

$$d\sigma(\theta) = d\sigma_0 \{W(\theta)\}$$



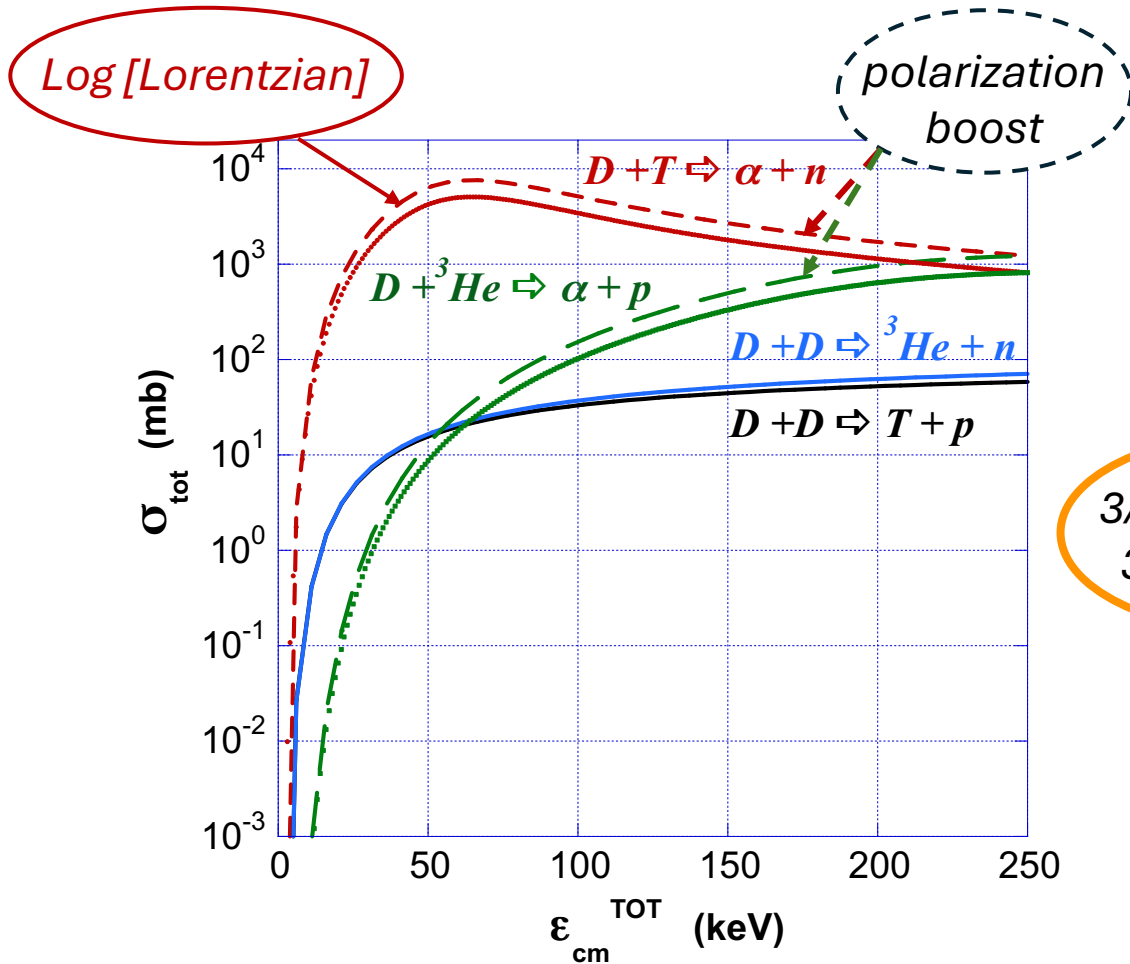
angle integrated cross section :

$$\sigma_{cm} = \sigma_0 \left\{ 1 + \frac{1}{2} \vec{P}_D^V \cdot \vec{P}_{^3He} \right\}$$

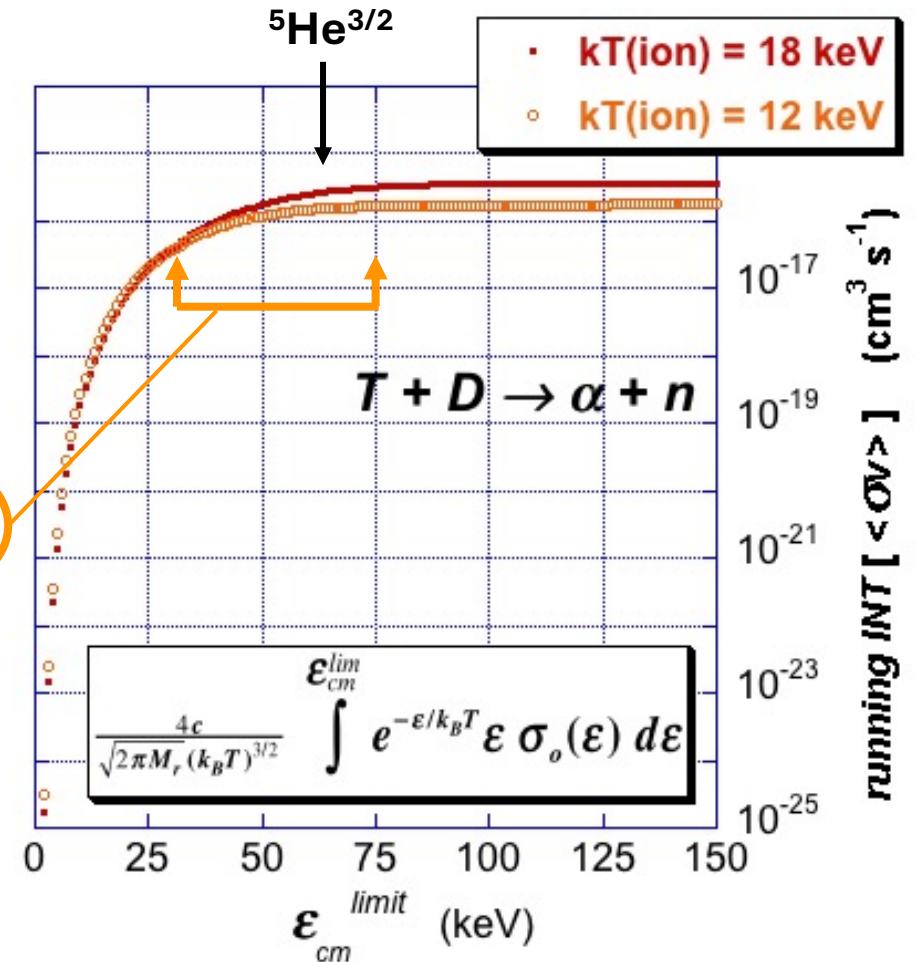
→ 50% increase in cross section
for fully polarized fuel,
for the same plasma parameters

Fusion reactions from the low energy tails of spin $J=3/2$ resonances

$$R = n_D n_T V_{pl} \times \left\{ \langle \sigma v \rangle = \frac{4c}{\sqrt{2\pi M_r} (k_B T)^{3/2}} \int e^{-\varepsilon/k_B T} \varepsilon \sigma(\varepsilon) d\varepsilon \right\}_{\text{maxwellian}}$$

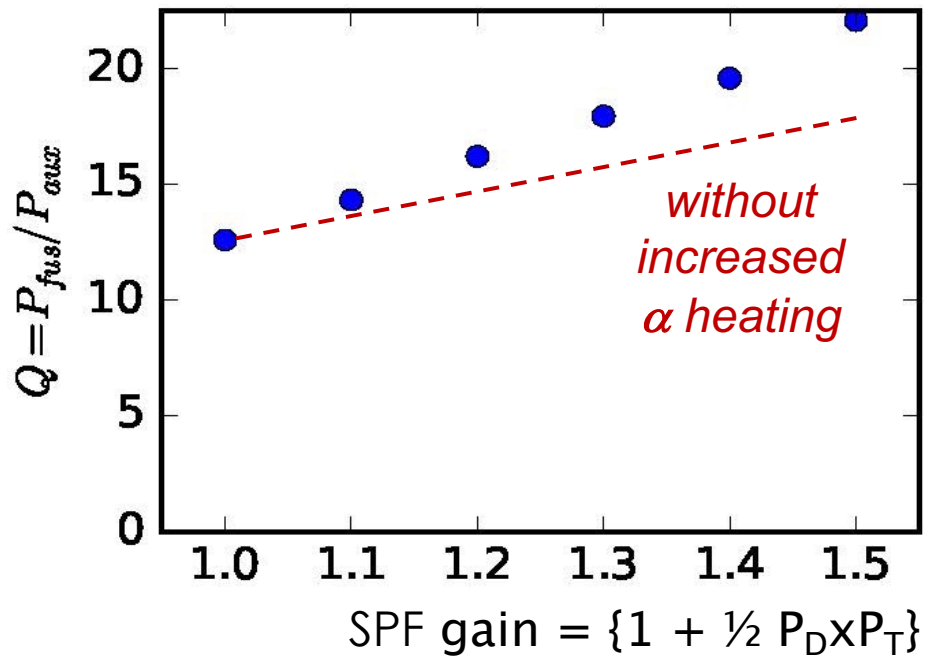


3/4 of Rate from
30 -to- 75 keV



Running up the low-energy tail: alpha heating $\Leftrightarrow$ non-linear enhancements

- polarization increases the reaction cross section
 - $\Leftrightarrow$ increases alpha production, which is mostly confined
 - $\Leftrightarrow$ alpha collisions heat the plasma $\Leftrightarrow$ higher temperature runs σ further up the resonance
- ITER Power simulations with polarized fuel: [Baylor *et al.*, Nucl. Fusion **63** (2023) 076009]
 - $\Leftrightarrow$ net 75% gain in power and $Q = P(\text{fusion})/P(\text{in})$

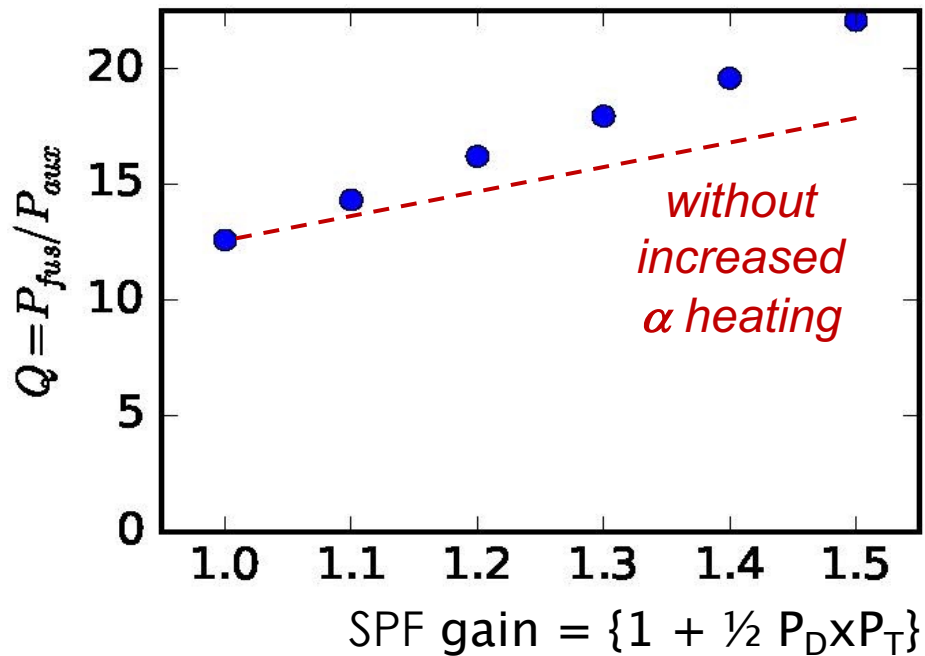


Long term – Fusion Power reactors:

- establish a controlled plasma in a 500 MW reactor
- switch to polarized fuel:
 - $\Leftrightarrow$ get 900 MW for the same plasma parameters

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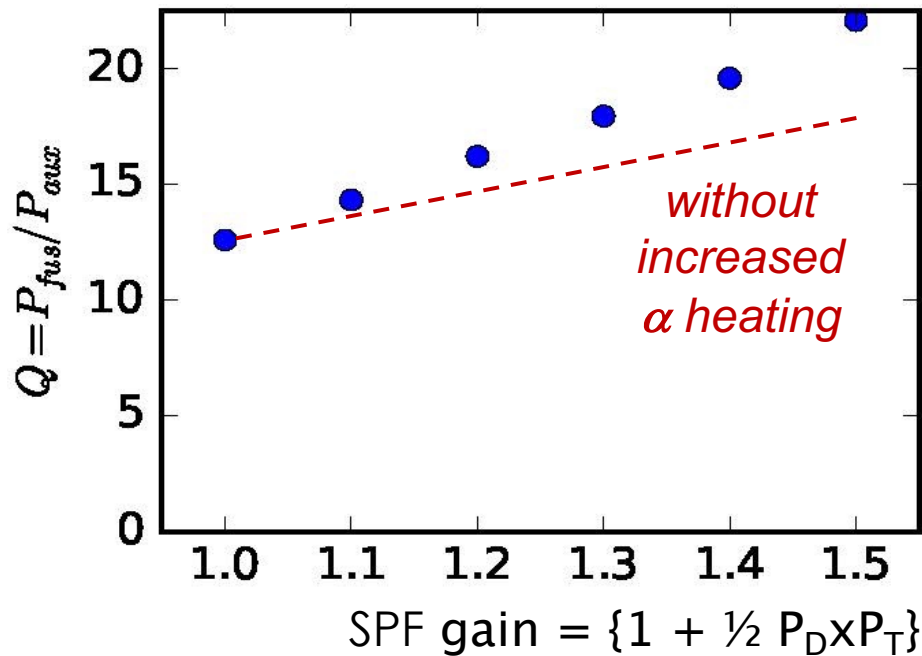


Long term – Fusion Power reactors:

- or
 - reduce tritium inventory by an order of magnitude
 - using a lower tritium fraction drives non-linear enhancements in burn eff, but reduces power
 - could maintain 500 MW by compensating with increased σ from SPF
- [Parisi, Diallo, Schwartz, arXiv:2406.05970 (2024)]

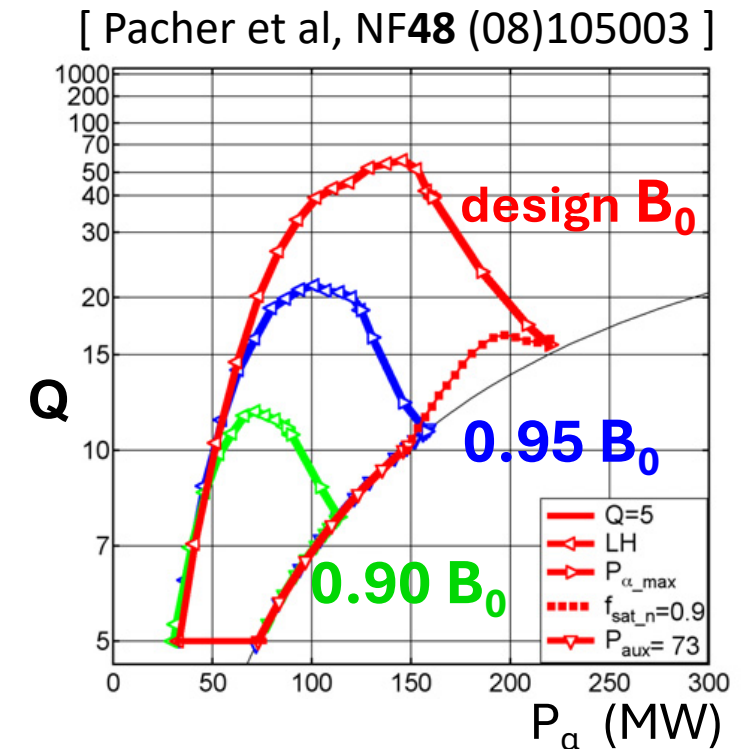
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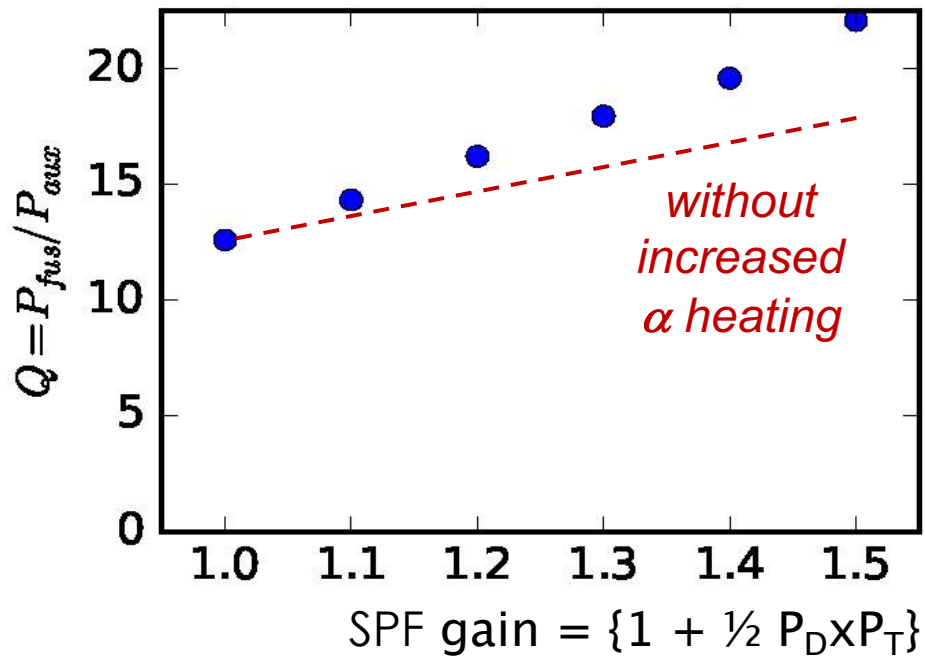
Prototype machines:

- eg. field degradation would severely limit ITER parameter space
 - polarization gain is independent of B
- $\Leftrightarrow$ SPF can compensate for field degradation



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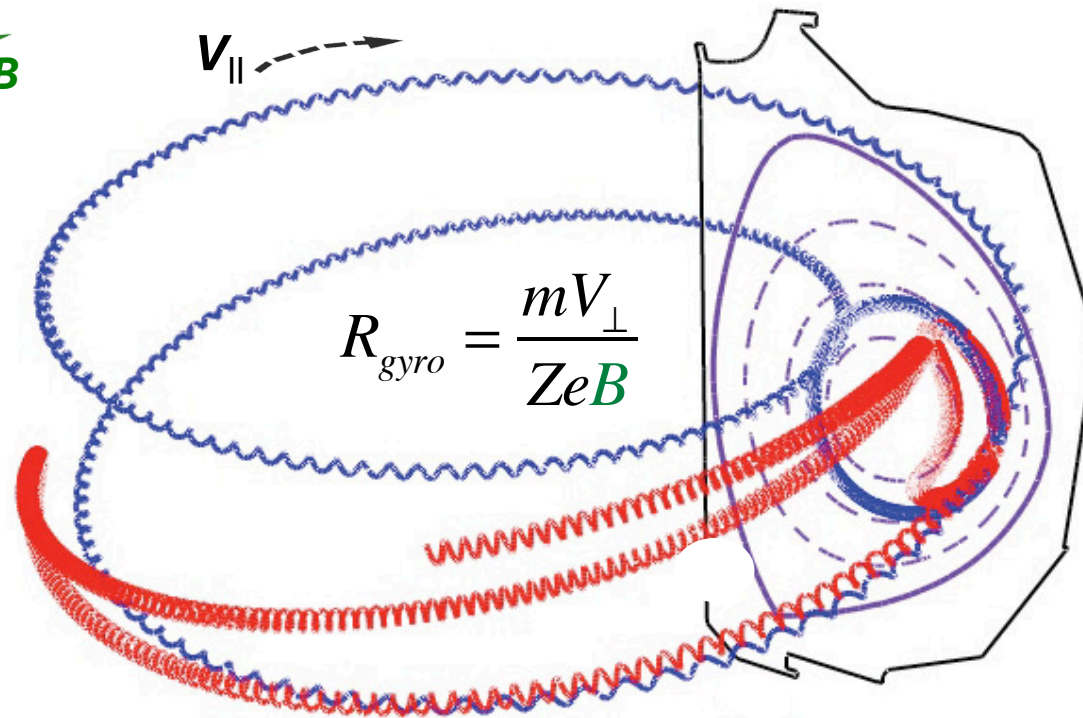
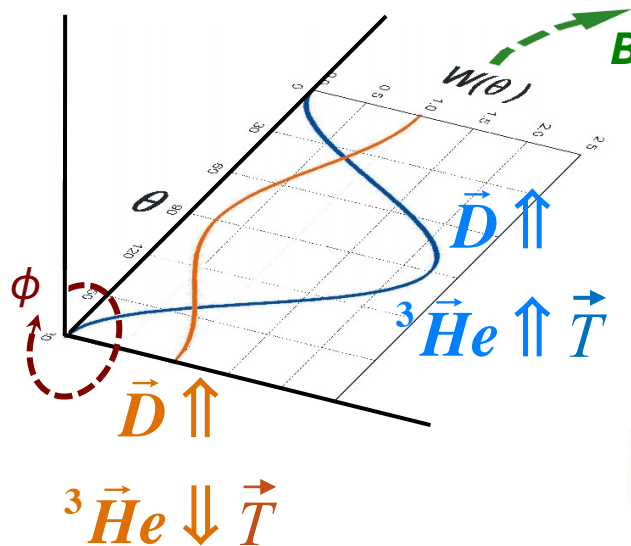


- There should be a similar non-linear gain from polarization in ICF
 - polarization increases the α yield
 - increased α collisions raise the temp
 - $\Leftrightarrow$ further increases the cross section, ... all for the same laser parameters !
- how big an effect in ICF – calculations ?

MCF: can anisotropy help ?

Kulsrud et al, PRL 49 (82):

- “the ability to control the anisotropy of the emitted α particles allows enhancement of the fraction trapped into well-confined orbits” $\Leftrightarrow$ **ie. might gain from increased α -heating, despite smaller $\sigma(\uparrow \downarrow)$** – NOT what we found in our sims [Baylor et al, NF 63 (2023) 076009]
- “shielding and blanket design would benefit ... by minimizing neutron load... on the wall”



...BUT,

$W(\theta)$ is independent of azimuthal / gyro-phase angle.

$\Leftrightarrow$ filling all phase-space requires rotating $W(\theta)$ around local B field

$\Leftrightarrow$ complicated trade-offs
need full simulations

(3) Polarized Materials used in Nuclear/Particle Physics & Medical Imaging

- Polarized Solids: material brought to high-B and low temp where equilibrium polarization is large
- three-step process: “*Dynamic Nuclear Polarization*” (DNP) [Goertz..., Prog Part Nucl Phys **49** (2002) 403]
 - (i) create paramagnetic centers (free electrons) by chemical doping ($\sim 1\%$) or by irradiation;
 - (ii) polarize free electrons at high-B/low-T ;
 - (iii) transfer spin alignment from e^- to H/D/(T) with μ -waves

eg: material	B(tesla) / T(K)	P(H/D)	
La ₂ (Mg) ₃ (NO) ₃ (H ₂ O) ₂₄	2.0 / 1.5	70 %	
C ₂ H ₄ (OH) ₂ , C ₂ H ₆ (OH) ₂ ,	2.5 / 0.5	99 %	<i>Ionizing the heavier elements that accompany polarized H / D will absorb energy and tend to quench a plasma</i>
H-Butanol C ₄ H ₉ OH	2.5 / 0.3	93 %	
D-Butanol C ₄ D ₉ OD	5.0 / 0.2	70 %	
H-Ammonia NH ₃	5.0 / 1.0	98 %	
D-Ammonia ND ₃	3.5 / 0.3	50 %	
Lithium-Deuteride LiD	6.5 / 0.2	70 %	⇔ <i>Lithium regularly used in tokamaks to suppress ELMs</i>

(3) Polarized Materials used in Nuclear/Particle Physics & Medical Imaging

- Polarized Solids: material brought to high-B and low temp where equilibrium polarization is large
 - two-step process: *Frozen-Spin HD* [Bass et al, NIM A737 (2014) 107; Baylor et al, NF 63 (2023) 076009]
 - (i) polarize *deuterium-hydride* at high-B/low-T
 - (ii) wait (~ weeks to months) for a frozen-spin state to set in for handling at low-B / high-T

eg: material	B(tesla) / T(K)	P(H/D)
HD	(i) 15.0 / 0.01	60 % H & 20% D
	(ii) 0.1 / ~ 3.0	20 % H & 40% D after RF spin transfer

- Polarized gases:
 - *Stern-Gerlach* atomic beams: H, D, HD, ... P(H,D) ~ 90% [Ralf Engels ..., PRL 124 (2020) 113003]
 - intensities limited to $\sim 10^{17} \text{ s}^{-1}$ $\Leftrightarrow$ would require a long collection time to accumulate enough material
 - Polarized ^3He :
 - *Spin Exchange Optical pumping* (SEOP): P(^3He) = 85% [Chen ...Gentile ... J. Appl Phys 116 (2014) 014903]
[Mooney, Wilson Miller, ... Proc Soc Magn Reson Med 17 (2009) 2166]
 - *Metastable Exchange Optical pumping* (MEOP): P(^3He) = 70% [Hussey ...Gentile... RSI 76 (2005) 053503]

(4) Depolarization mechanisms (MCF)

- **depolarization immediately following injection:**

from hyperfine mixing between a bound electron and aligned nucleus

- (Baylor *et al.*, 2023 Nucl. Fusion [63](#), 076009)

$$\frac{\Delta P}{P} = \frac{1}{2} \left[1 + \frac{4(\mu_e - \mu_{ion})^2}{A_{HFI}^2} B^2 \right]^{-1} < 1\% \text{ for DIII-D}$$

- **polarization loss during particle confinement period:**

- Kulsrud, Valeo and Cowley,

Physics of spin-polarized plasmas, 1986, Nucl. Fusion [26](#), 1443

- Gatto, *Depolarization of Magnetically Confined Plasmas*

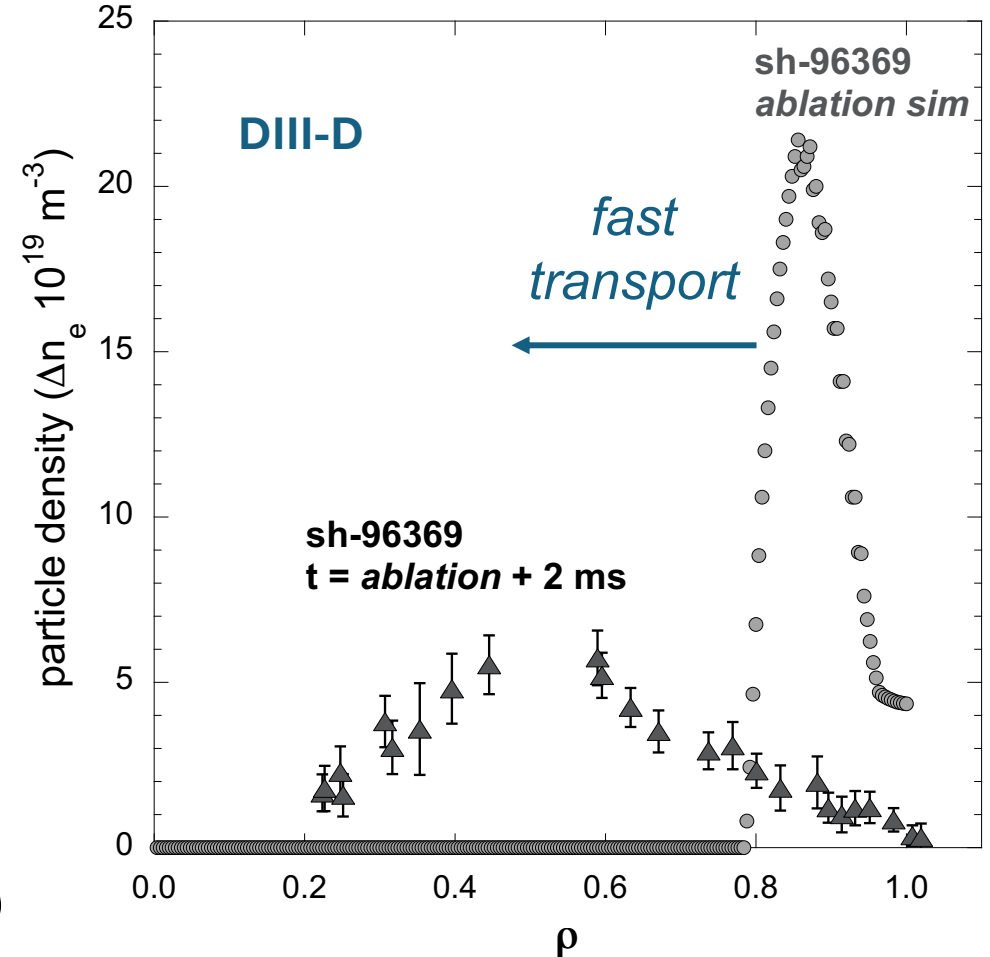
Nuclear Fusion with Polarized Fuel, 2016 Springer Proc. Phys. vol [187](#), 79

⇔ **two mechanisms survive scrutiny:**

- **wall recycling**
- **resonant interactions with plasma waves**

Wall recycling (MCF):

- Modern tokamaks fueled by pellet injection
 - ⇔ particles reach the core ~immediately
- small fraction react within confinement time τ_p (0.1 - 0.2 s in DIII-D; 4 - 8 s projected for ITER)
- most leave the plasma; can depolarize at walls
 - ⇔ dilutes polarization if they re-entering plasma
- Mid-Scale Research machines (eg. DIII-D)
 - recycling will limit measurable Pol life-time range
 - depolarization low for carbon walls (present DIII-D)
 - treating wall surface with a *getter* (Li, B) reduces recycling significantly. (BIG impact on confinement)
- High-power ITER-scale machines
 - Scrape-off-layer essentially opaque to neutrals (2012 Garzotti *et al*, NF52, 013002)
 - THERE WILL BE ~ NO WALL RECYCLING IN A POWER REACTOR



Plasma waves

- spins precess around the magnetic field at the Larmor angular frequency, $\omega_L = \left(\frac{\gamma}{2\pi}\right) B$
 $\Leftrightarrow$ there is a potential for depolarization if the frequency of a plasma wave matches ω_L

- ions orbit at cyclotron angular frequency, $\omega_c = \frac{Ze}{2\pi M} B$

	D	T	³ He
ω_L / ω_c	0.86	8.92	-3.18

- Lodder, Phys Lett A98 (83) 179 $\Leftrightarrow$ big issue

- Kulsrud, Valeo, Cowley, NF26 (86) 1442 $\Leftrightarrow$ small issue

- Heidbrink *et al*, Frontiers Phys (2024) 1355212 $\Leftrightarrow$ ion-cyclotron RF (ICRF)

- externally-launched ICRF for plasma heating:

- in tokamaks such as DIII-D, B falls as 1/R,

- ICRF* can be configured to match precession frequencies near the wall or outside plasma

- *ICRF* should still be possible in *mirror* machines, such as WHAM

- but large field variations in spherical tokamaks could be serious $\Leftrightarrow$ Kate Borowiec ?

- instabilities in the ICRF are of greater concern, These might propagate to regions where their frequencies match ω_L , potentially driving depolarization. Polarization lifetime experiments are needed to explore useful operating regimes.

(5) Potential for large-scale fueling of a power reactor with fully polarized fuel

- **Conventional polarized atomic-beam sources**

- produces a *stream* of polarized particles by magnetically selecting (*ie. Stern-Gerlach*) the spin alignment of interest. Limited by multiple scattering to $\sim 10^{17} \text{ s}^{-1}$

- **New high-flux laser-driven molecular sources** $\Leftrightarrow$ as in talk by **Peter Rakitzis**

- polarization happens within each molecule
- multiple-step process; each step has been demonstrated at low laser powers
- industrial-power lasers could yield a *tsunami* of polarized particles with fluxes of $\sim 10^{22} \text{ s}^{-1}$ with $\sim 100\%$ polarization

$\Leftrightarrow$ extensive R&D to verify power scaling

Status in the 1980s:

- subsequent work all but died out because:

(1) technical challenges in testing polarization survival:

- few options for polarizing hydrogens
 - ⇔ only optically-pumped atomic gas beams, too low intensities for either MCF or ICF
- MCF: only injection option was gas puffing:
 - ⇔ difficult to reach the plasma core directly
 - ⇔ multiple wall collisions likely to depolarize
- ICF: difficult to prepare an ICF pellet
 - ⇔ from NP, depolarization rate of polarized gas ~ surface/volume ratio & vessel coating

(2) large-scale fueling of a power reactor beyond reach

Status today

✓ options from NP & Med:

- solid polarized HD, LiD
- high pressure pol 3He

✓ pellet injection routine

- fast transport to core
- wall coatings

✓ options from NP

- solid polarized HD, LiD

✓ laser source potential

(6) The DIII-D Polarization Survival Experiment

D + ³He as a test-bed for Spin-Polarized-Fusion:

In nuclear reactions, isospin is a very good quantum number, particularly at low energies

⇔ ⁵He and ⁵Li are *mirror* nuclei with virtually identical low-energy structure

⇔ $D + T \rightarrow {}^5\text{He} \rightarrow \alpha + n$ and $D + {}^3\text{He} \rightarrow {}^5\text{Li} \rightarrow \alpha + p$

are mirror reactions, with the same spins, incorporating the same nuclear physics

⇔ Polarization survival can be tested with $D + {}^3\text{He} \rightarrow \alpha + p$ (avoiding complications of tritium)

Overview of a SPF Demonstration Experiment:

- L. Baylor, A. Deur, N. Eidietis, W.W. Heidbrink, G.L. Jackson, J. Liu, M.M. Lowry, G.W. Miller, D. Pace, A.M. Sandorfi, S.P. Smith, S. Tafti, K. Wei, X. Wei and X. Zheng, NF **63** (2023) 076009
⇔ *experimental design, simulated polarization signal from change in yields*
- A.V. Garcia, W.W. Heidbrink, A.M. Sandorfi, NF **63** (2023) 026030
⇔ *simulated polarization signal from change in angular distributions*

Spin-Polarized-Fusion Collaboration

Jefferson Lab

(Polarized D Fuel)

X. Wei, P. Dobrenz, D. Williams



University of Virginia

(Polarized ^3He Fuel)

G. W. Miller, A. M. Sandorfi, X. Zheng, A. Nelsen, S. Patel,
E. Gunasekara, G. Cates, H. Nguyen



Oak Ridge National Lab

(Polarized Fuel injectors)

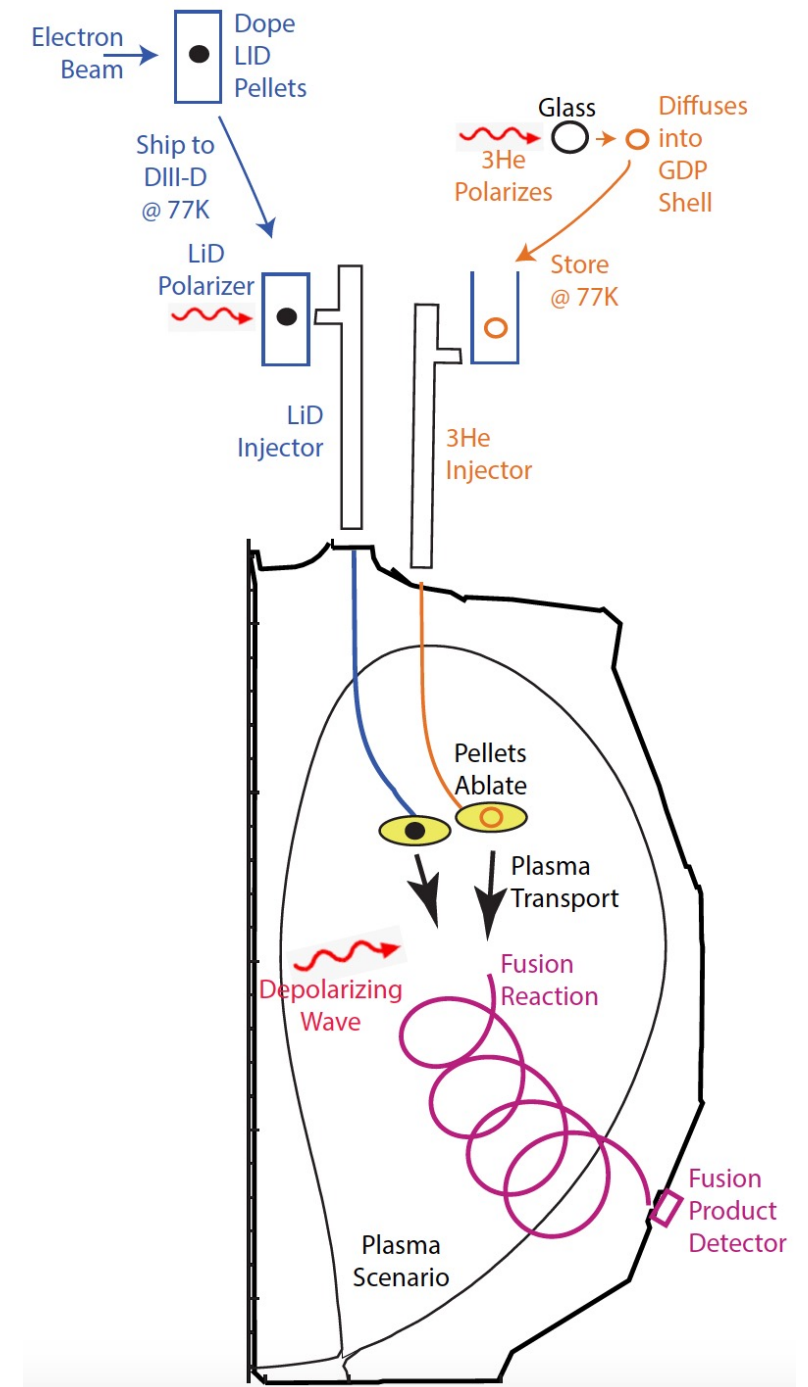
L. Baylor, S. Meitner, ...



University of California, Irvine

(Fusion product detection and Diagnostics)

W. Heidbrink, ...



General Strategy:

- use existing NP and Imaging techniques to create polarized fuels with sufficient life-times for a direct *in-situ* test of SPF in a high- T_{ion} plasma within the DIII-D tokamak
 - ⇔ not the fuel for a power reactor, but it mitigates costs in a life-time demonstration exp that can explore the useful operating regimes for SPF

- polarized D (*small NP targets*)

solid **LiD** cylinders: - 3.0 mm X 1.5 mm OD ; $n(D) \sim 3 \times 10^{20}$

- DNP ⇔ $P^V(D) = 70\%$, $P^T(D) = 41\%$; injected at 4K ⇔ $T_1 \sim 6$ min

- polarized ^3He

pressurized gas:

- encapsulated in 3.0 mm OD x ~ 20 μm wall polymer shells at 25 atm

- SEOP ⇔ $P(^3\text{He}) = 65\%$; $n(^3\text{He}) \sim 0.1 \times 10^{20}$

- injected at 77 K ⇔ $T_1 \sim 3$ days

$$\Leftrightarrow \sigma_{\uparrow\uparrow} / \sigma_{\uparrow\downarrow} (\text{Li D} + ^3\text{He}) = 1.6 \quad [\text{Baylor et al, NF } \mathbf{63} \text{ (2023) 076009}]$$

DOE-FES FUNDING – start Sept/2023

⇔ *Xiangdong Wei will outline our progress to date*

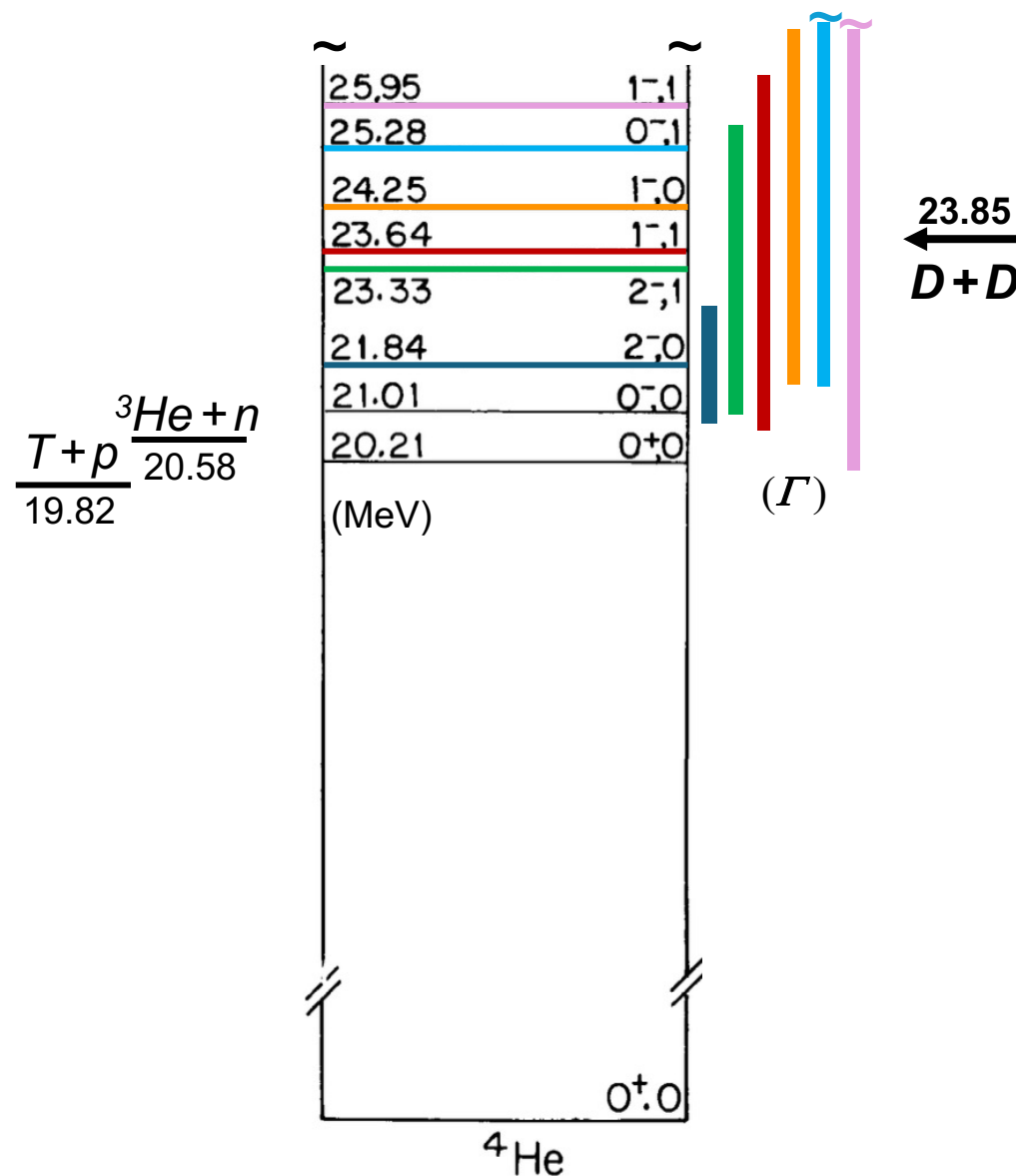
⇔ *Bill Heidbrink will discuss detection options and schedule*

(7) Other options for testing polarization survival

- most MCF & ICF run with D plasmas

? $\vec{D} + \vec{D} \Rightarrow {}^4\text{He} \rightarrow {}^3\text{He} + n$ or $T + p$?

- D+D feeds a large number of broad (Γ) overlapping levels in ${}^4\text{He}$ $\Leftrightarrow$ large interference effects, further complicated by the deuteron D -state



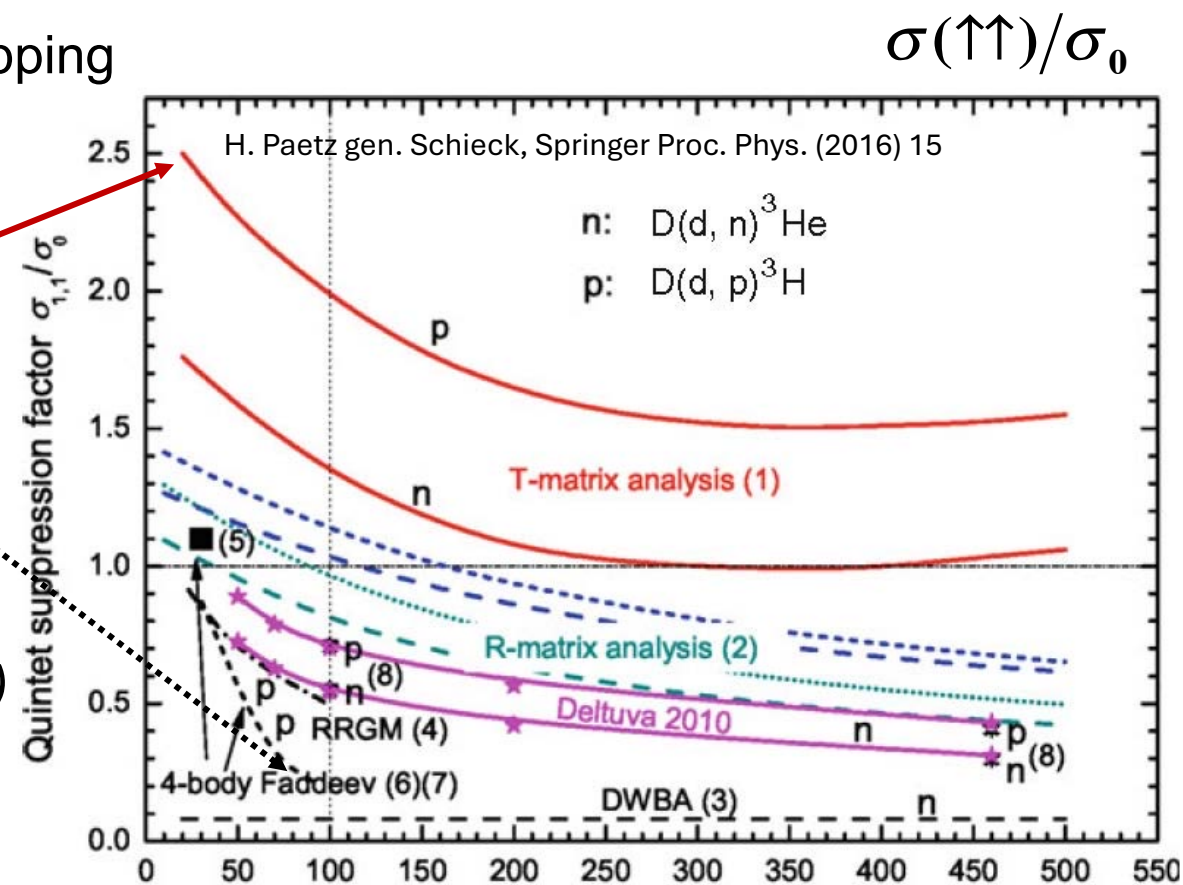
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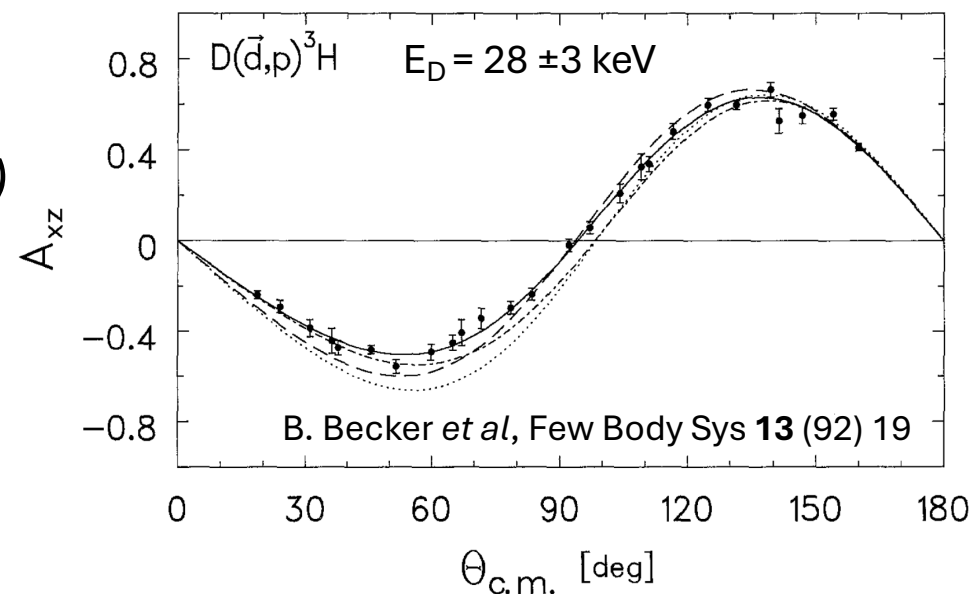
- D+D feeds a large number of broad (Γ) overlapping levels in ${}^4\text{He}$ $\Leftrightarrow$ large interference effects, further complicated by the deuteron D -state
- NP theory predictions for $\sigma(\uparrow\uparrow)/\sigma_0$ range from enhancement by 2.5 to suppression by 10
- 1st direct measurement with polarized beams and targets in preparation at PNPI-Gatchina (St Petersburg) with Ferrara and Juelich

$\Leftrightarrow$ update from Giuseppe Ciullo ?



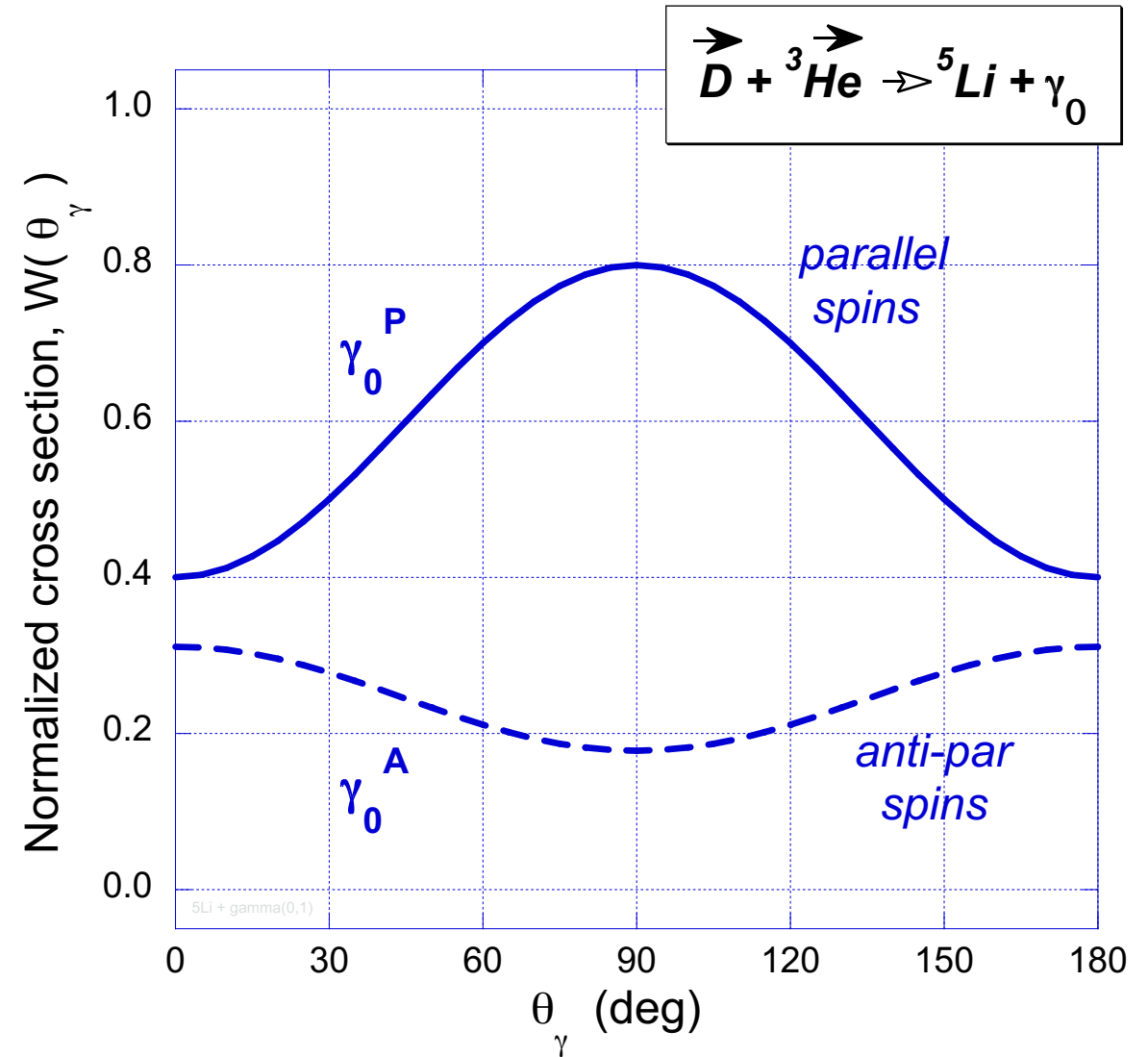
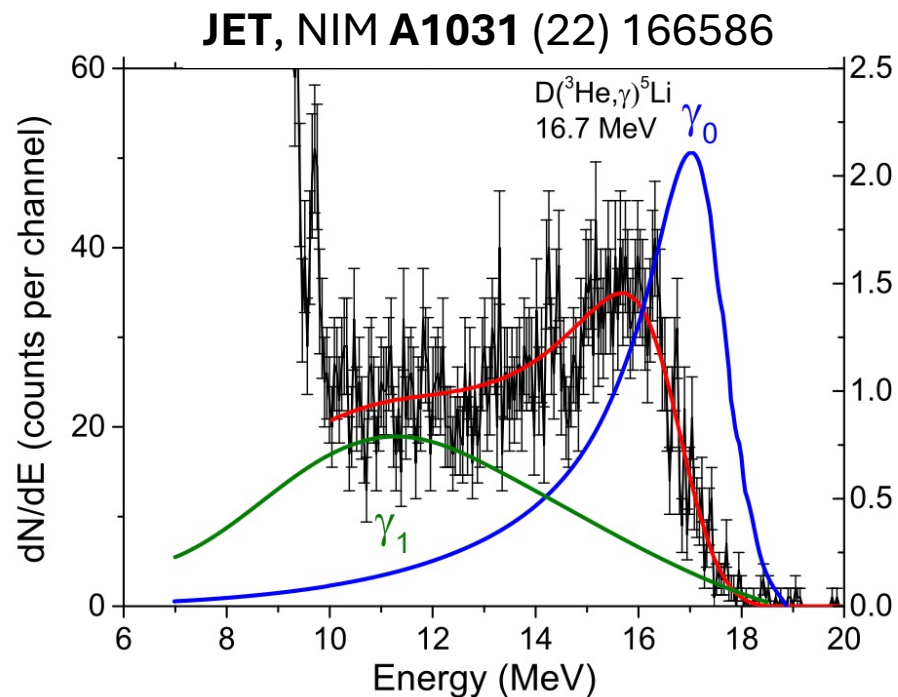
(7) Other options for testing polarization survival

- what about $\vec{D} + D$
 - polarization asymmetry data (NP “Analyzing powers”) available down to thermal plasma temperatures
 - However, combining polarized $\vec{D}$ with unpolarized D at the same plasma temperature just dilutes the deuteron polarization $\Leftrightarrow$ small signal
 - option for MCF:
 - $\Leftrightarrow$ inject polarized (a) $\vec{D}$ pellets into a ^4He or H plasma, and (b) 80 keV neutral D beam $\Leftrightarrow$ higher energy $\Leftrightarrow$ higher cross section
 - A.V. Garcia, W.W. Heidbrink, A.M. Sandorfi, NF (submitted)
- $\Leftrightarrow$ will be discussed by Bill Heidbrink





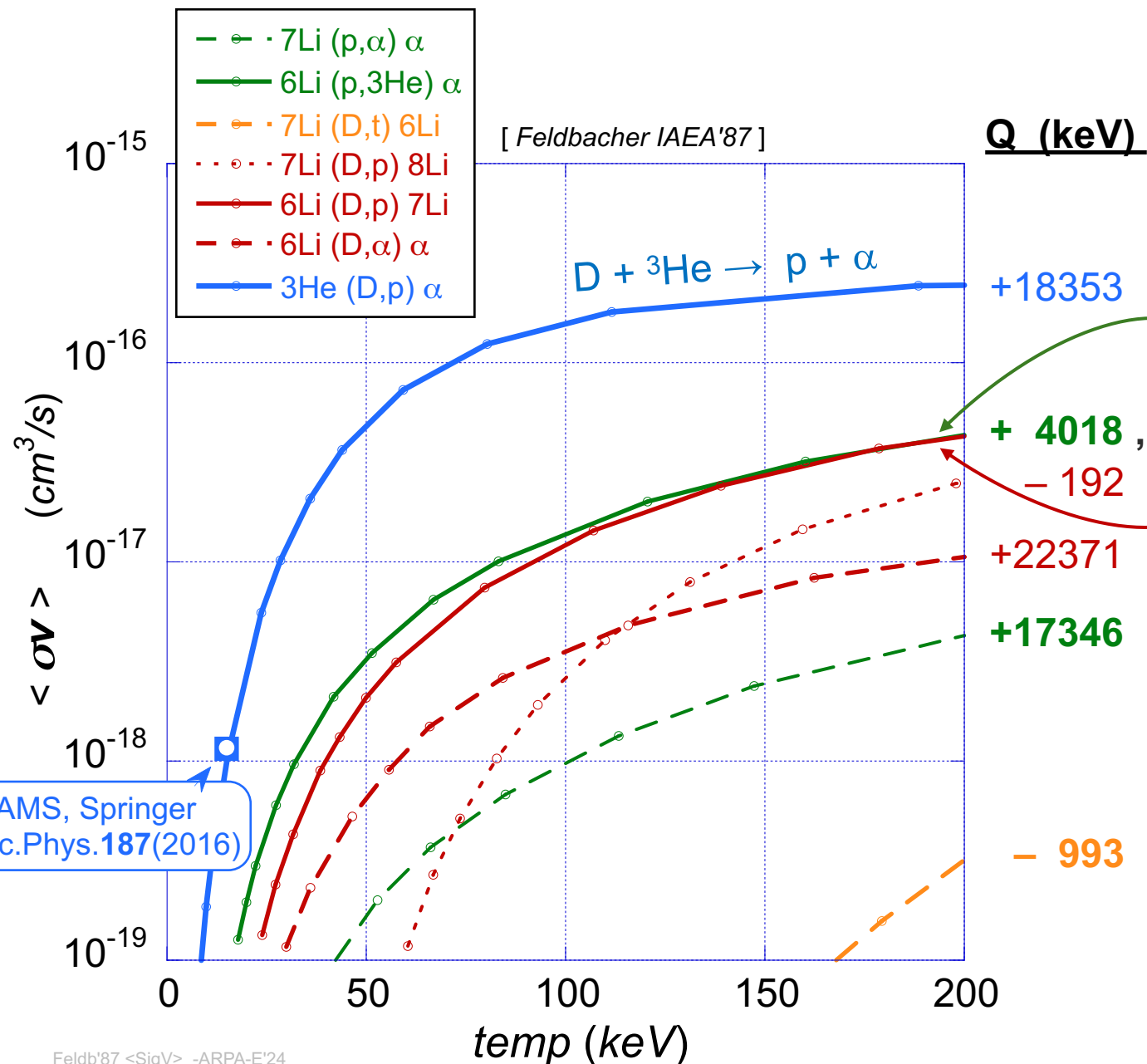
- lines broadened by width of final states in ${}^5\text{Li}$
 $\Gamma_0^{\text{cm}}(\text{g.s.}) = 1.2 \text{ MeV}$; $\Gamma_1^{\text{cm}}(1^{\text{st}}) = 6.6 \text{ MeV}$
- $\Leftrightarrow$ high-resolution needed with NaI
 (at 16 MeV, $\sim 2.5\% = 0.4 \text{ MeV}$ is possible)
- count-rate low, but background very low



[Garcia, Heidbrink, Sandorfi, NF **63** (2023) 026030]

Possible ICF test reactions

⇔ need 2 polarized species in one pellet



- with Li H / Li D, both lithium and hydrogen can be polarized simultaneously

- issues to investigate:
 - uniformity of material
 - availability of ${}^6\text{Li}$ D from Y-12

Summary

- Polarized fusion fuels increase reaction cross sections by 1.5, and could increase Q/power in an ITER-scale MCF reactor by 1.8 due to alpha heating
⇔ boosts power, decreases plant costs, potentially BIG decrease in tritium inventory
- gains come for the same plasma parameters ⇔ no R&D to change operating conditions
⇔ immediate increase in power ⇔ can compensate for complications in prototype machines
- new laser-pumped molecular sources have the potential for large-scale fueling of a power reactor with 100% polarized fuel, but appreciable R&D is required
- Polarization lifetime measurements in realistic MCF / ICF conditions are crucial
⇔ leverage polarized materials developed for Nuclear/Particle Physics and Medical-Imaging
- Major project underway to measure SPF in the DIII-D tokamak with $D+{}^3\text{He} \rightarrow \alpha+p$, the mirror reaction to $D+T \rightarrow \alpha+n$, using separate pellet injectors for polarized D and ${}^3\text{He}$
- ICF challenge: prepare two polarized species in a single pellet ⇔ possible options from LiD