Spin polarized fuel in tokamak fusion reactors

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Injecting spin polarized fuel in an existing tokamak would inform the possibility of enhanced future tokamaks

- Spin polarizing the fuel in the most favorable fusion reaction
  \[ \text{D + T} \rightarrow \text{^{5}He} \rightarrow \alpha + n \ (+17.6 \text{ MeV}) \]
  yields up to a factor of 1.5 greater cross section for this reaction

- In the power balance of a future tokamak reactor, a 50% increase in cross section leads to a 75% increase in fusion power

- The polarization survival should be testable in DIII-D by injecting spin polarized HD and \(^{3}\text{He}\) pellets and measuring the quantity and distribution of fusion products on the tokamak wall from
  \[ \text{D + ^{3}He} \rightarrow \text{^{5}Li} \rightarrow \alpha + p \]
Outline

• What is a tokamak?

• Nuclear physics of spin polarized fusion

• Implications for future reactors

• Testing spin polarization survivability in DIII-D
Tokamak = Toroidal Confinement by Magnetic Fields

- The toroidal guide field is produced by external coils
- The poloidal field is produced by driving current toroidally in the plasma
- Helically winding magnetic field lines trace out a flux surface
- The plasma particles are confined long enough to undergo fusion
DIII-D is a medium sized, but well diagnosed tokamak

- $B_T < 2.1 \, T$, $I_p < 1.5 \, MA$
- $R = 1.6 \, m$, $a = 0.6 \, m$
- H, D, or He Fuel
- Elect. Dens. $\sim 5 \times 10^{19}/m^3$
- Elect. Temp. $< 12 \, keV$
- Ion Temp. $< 18 \, keV$
- 15 MW Neutral Beams
- 3 MW Electron Cyclotron Heating
- Discharge current flat-top 5-10 s
- 1 discharge (shot) per 12-15 minutes

DIII-D tokamak (San Diego / USA)
ITER is the next step device being built in France

Where’s Waldo?

DIII-D
Pitch (polar) angle of fusion products relative to the magnetic field matters in a tokamak

- Pitch angle closer to 0 or 180 degrees: **passing** particle stays closer to magnetic field line and samples all of the flux surface – confined longer to give energy to thermal plasma
- Pitch angle closer to 90 degrees: **trapped** particle has large excursions from the flux surface and doesn’t sample inboard.
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Reactor Performance can be Improved by Exploiting the Dependence of Fusion Cross-section on Spin Polarization

Fusion Reaction

\[ \text{D + T} \rightarrow \alpha + n (+17.6 \, \text{MeV}) \]

Reaction Rate, \( R \) (s\(^{-1}\))

\[ R = n_D \, n_T \, V_{\text{plasma}} \langle \sigma v \rangle \]

Isotropic Spin Distribution

\[ \int \sigma \rightarrow \sigma_0 \]

Spin Polarized Distribution: parallel to B

\[ \int \sigma \rightarrow 1.5 \, \sigma_0 \] 50% fusion rate increase for full polarization

Studying the $D + {}^3He$ Reaction Addresses the Physics Necessary for Application to $D + T$ Reactions

$D + T \to {}^5He \to \alpha + n \quad D + {}^3He \to {}^5Li \to \alpha + p$

- Isospin (neutron/proton equivalence) is a very good quantum number, particularly at the low energies of particles in a tokamak
  - $^5He$ and $^5Li$ are mirror nuclei with nearly identical low-energy structure
  - $D+T$ and $D+{}^3He$ reactions are mirror reactions with same spins and same nuclear physics
Polarization Leads to a Non-isotropic Fusion Cross-section

- Inject polarized fuel into a tokamak

\[
\text{D} + ^3\text{He} \rightarrow ^5\text{Li} \rightarrow \alpha + p
\]

parallel spins \( \vec{D} \uparrow ^3\text{He} \uparrow \):
\[
\frac{d\sigma}{d\Omega_{cm}} = \left( \frac{d\sigma}{d\Omega} \right)_0 \left\{ \frac{9}{4} \sin^2 \theta \right\}
\]

antiparallel spins \( \vec{D} \uparrow ^3\text{He} \downarrow \):
\[
\frac{d\sigma}{d\Omega_{cm}} = \left( \frac{d\sigma}{d\Omega} \right)_0 \left\{ \frac{1}{4} (1 + 3 \cos^2 \theta) \right\}
\]

- Pitch angle \((\theta)\) of the charged fusion products relative to the magnetic field is skewed
  - parallel spins produce more trapped particles
  - anti-parallel spins produce more passing particles
(Anti-) Aligning Spins Yields (-)+50% Change in Fusion Rate

- Angle-integrated fusion cross-section:
  \[
  \sigma_{\text{cm}} = \sigma_0 \left\{ 1 + \frac{1}{2} \vec{P}_D^V \cdot \vec{P}_3^{\text{He}} \right\}
  \]

- Fully polarized fuel:
  \[
  \left| \vec{P}_D^V \right| = 1 , \quad \left| \vec{P}_3^{\text{He}} \right| = 1
  \]

- Resulting fusion rate is modified
  - both spins parallel to B:
    \[
    \sigma_{\text{cm}} = \sigma_0 \left\{ 1 + \frac{1}{2} \right\}
    \]
  - one spin parallel, the other anti-parallel to B:
    \[
    \sigma_{\text{cm}} = \sigma_0 \left\{ 1 - \frac{1}{2} \right\}
    \]
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Spin Polarized Fuel can Benefit Fusion Reactors by Improving either Power Generation or $\alpha$-particle Confinement*

- **Improving power generation**
  - D and T polarized $\parallel$ B
  - 100% polarization produces fusion rate increase of 50%
  - $\alpha$-particle birth pitch angle
    \[ N(\theta_{\alpha}) \sim \sin^2(\theta_{\alpha}) \]

- **Enhanced $\alpha$-particle confinement**
  - D polarized $\perp$ B
  - \[ N(\theta_{\alpha}) \sim 1 + 3 \cos^2(\theta_{\alpha}) \]
  - larger passing $\alpha$-particle population

Spin Polarized Fuel can Makeup for Magnetic Field Degradation in Superconducting Tokamaks

- Recast the fusion rate in terms of magnetic field

\[ R = n_D n_T V_{\text{plasma}} \langle \sigma v \rangle \]
\[ = \frac{\beta^2 B^4}{4 \mu_0^2 T^2} V_{\text{plasma}} \langle \sigma v \rangle \]

- 50% increase in reaction rate is equivalent to as much as a 11% increase in magnetic field for ITER
  - improve Q at targeted magnetic field
  - reach Q = 10 even if facing toroidal field degradation

Increase in Fusion Power Scales Faster than the Reaction Rate

- Fusion alphas heat a reactor through collisional damping on electrons and ions.
- Increased fusion alpha heating increases the plasma temperature.
- Increased plasma temperature further increases fusion rate until a new power balance is reached.
- Fusion rate increase of 1.5 → fusion power increase of 1.75.
Polarized Fuel has the Potential to Significantly Reduce Reactor Cost

- **Fuelling a 500 MW plasma in ITER**
  - 5 mm outer diameter pellets of separate D and T injected at 7 Hz
  - 2000 mol/day of each species at 100% polarization

- **If these quantities of polarized fuel are available**
  - equivalent to ~15% magnetic field increase
  - tokamak reactor cost scales as \( B^2 \)
  - reactor cost is reduced by ~30%

Next Step in SPF Research is to Demonstrate that the Fuel Remains Polarized Longer than a Confinement Time

• SPF benefits require that polarization persists in the tokamak long enough for fusion to occur
  – energy splitting between polarization states is minuscule: \[10^{-10} \text{ keV} \ll T_{\text{ion}}\]

• Many depolarization mechanisms have been explored, but survival is expected (collisions and recycling are small depolarization mechanisms)*
  – Recent ITER modeling predicts that wall recycling will be negligible for its hot plasma conditions

• We propose that polarization survival should be tested in current devices with current polarization techniques

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• Testing spin polarization survivability in DIII-D
• Prepare polarized deuterium with existing Jefferson Lab facilities: solid $^{2}H^{3}D$ pellets
  – diffuse 200 - 400 atm HD into shells (Inertial Confinement Fusion ICF type from General Atomics)
  – cool gas to reach solid state
  – polarize both H and D
  – spin transfer H $\rightarrow$ D for maximum D polarization
  – fired from 2 K pellet launcher at DIII-D
Prepare polarized deuterium with existing Jefferson Lab facilities: solid $H\bar{D}$ pellets

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*standard technology well established in nuclear physics experiments*
• Prepare polarized deuterium with existing Jefferson Lab facilities: solid $^2$H$^3$D pellets
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• Develop polarized $^3$He with existing U. Virginia facilities: gas-filled ICF-type pellets
  – build equipment to reproduce procedure at DIII-D
  – fired from 77 K pellet launcher
• Prepare polarized deuterium with existing Jefferson Lab facilities: solid $H\tilde{D}$ pellets
  – diffuse 200 - 400 atm HD into shells (Inertial Confinement Fusion ICF type from General Atomics)
  – cool gas to reach solid state
  – polarize both H and D
  – spin transfer H $\rightarrow$ D for maximum D polarization
  – fired from 2 K pellet launcher at DIII-D

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DIII-D Experiments could Confirm Polarization Lifetime by Comparing Fusion Product Yields

standard technology well established in nuclear physics experiments

active research and technique development

$H\tilde{D} \uparrow + ^3\tilde{He} \uparrow$

$H\tilde{D} \downarrow + ^3\tilde{He} \uparrow$
• Prepare polarized deuterium with existing Jefferson Lab facilities: solid $^2$H$^2$D pellets
  – diffuse 200 - 400 atm HD into shells (Inertial Confinement Fusion ICF type from General Atomics)
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• Develop polarized $^3$He with existing U. Virginia facilities: gas-filled ICF-type pellets
  – build equipment to reproduce procedure at DIII-D
  – fired from 77 K pellet launcher

• Fire pellets with alternating spin alignment into appropriately high-T$_i$ plasma at DIII-D

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$H\bar{D} \uparrow + ^3\bar{He} \uparrow$

$H\bar{D} \downarrow + ^3\bar{He} \uparrow$
Consider realistic polarization fractions

\[
\begin{align*}
P_v(D) &= 0.40 & \text{JLab} \\
P(\overline{3}\overline{He}) &= 0.65 & \text{UVa}
\end{align*}
\]

Resulting fusion cross-sections produce a 30% difference in fusion rate

\[
\frac{\langle \sigma_{\text{par}} \rangle}{\langle \sigma_{\text{anti}} \rangle} = 1.30
\]

Trapped/passing population of the fusion products is also dependent on the spin-alignment
QH-mode Shot with $T_i(0) = 15$ keV is Modeled to Demonstrate Output Profile of Charged Fusion Products

- Start from ONETWO* calculations of D-D fusion rate for D pellet injected shot
- Convert to equivalent for D-$^3$He
- Scale up to high $T_i$ discharge

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*S.P. Smith et al./22nd International Spin Symposium/September 28, 2016*
Following fusion products of various birth locations and pitch angles reveals final losses to walls in DIII-D

- **Trapped** particles get preferentially lost to different locations than **passing** particles
Following protons of various birth locations and pitch angles reveals final losses to walls in DIII-D.

Ion Rate $10^{11}/(\text{m}^2\text{s})$
Ratio of parallel to anti-parallel proton fusion product poloidal distribution yields up to 30% change

Characteristic signature of SPF is poloidal dependence of Anti/Parallel proton ratio

Poloidal angle ($\psi$)
Following alphas of various birth locations and pitch angles reveals final losses to walls in DIII-D.
Ratio of parallel to anti-parallel alpha fusion product poloidal distribution yields up to 30% change.

Characteristic signature of SPF is poloidal dependence of Anti/Par alpha ratio.
• Prepare polarized deuterium with existing Jefferson Lab facilities: solid $^2$H$^2$D pellets
  – diffuse 200–400 atm HD into shells (ICF type from GA)
  – cool gas to reach solid state
  – polarize both H and D
  – spin transfer H $\rightarrow$ D for maximum D polarization
  – fired from 2 K pellet launcher at DIII-D

  standard technology well established in nuclear physics experiments

• Develop polarized $^3$He with existing U. Virginia facilities: gas-filled ICF-type pellets
  – build equipment to reproduce procedure at DIII-D
  – fired...

  active research and technique development

• Fire pellets with alternating spin alignment into appropriately high-T plasma at DIII-D

  $^{2}$H$^{2}$D $\uparrow \uparrow + ^{3}$He $\uparrow \uparrow$

  $^2$HD $\downarrow \downarrow + ^3$He $\uparrow \uparrow$

  signal-to-noise must satisfy certainty criterion
Scientific Demonstration of an SPF Effect May Require ~40 (Repeated) Plasma Shots

- Scientific demonstration achieved when effect is measured at $5\sigma$ certainty
- Expected significance level determined from Monte Carlo calculations
- Significance depends strongly on shot repeatability
  - 8% variation $\rightarrow$ 4 shots
  - 16% variation $\rightarrow$ 18 shots

\[ P(D) = 0.40; P(3\text{He}) = 0.65 \]

A.M. Sandorfi, et al., (to be published)
DIII-D Shots are Generally Reproducible, though it Remains to Demonstrate this for an SPF-relevant Plasma

- Repeating a shot produces the same result, even when considering instabilities

- High-performance discharges exhibit ~10% variability in peak temperatures*

- Need to determine the profile repeatability in a high ion temperature shot

\[ R \propto n_{He} n_D T_i \]

*G.L. Jackson, “DIII-D shot series with similar shots,” Internal Memo, December 9, 2014
Development of Spin Polarized Fusion (SPF) Could Yield Great Rewards; Further Research Needed

• SPF can reduce reactor costs through increased fusion rate at given plasma conditions

• Test of polarization lifetime can be achieved in DIII-D plasmas

• Companion work is leading to improved techniques for fuel preparation
Supplementary Slides
• $^3$He is polarized through spin-exchange optical pumping
  – Rb vapor pumped with 795 nm, 100 W laser in an oven at > 200 C
  – Rb transfers polarization to K by collisions
  – K transfers polarization to $^3$He by collisions

• Typical polarization is 70% @ 10 amagats (~10 atm)

• Large volume targets are used in Nuclear Physics experiments

• Challenge for the tokamak fuel
  – high power laser, polarize materials inside a glass cell
  – remove alkalis (~few ppm)
  – permeate through ICF-type shell
Experiments Confirm $^3$He Maintains Polarization During Permeation Process

- Cool to LN$_2$ to seal pellet
- Polarization decay
  \[ P_{\text{ICF}} = P_0 \left( 1 - e^{-\frac{t}{\tau}} \right) \]
- Permeation at 20 - 200 C
Experiments Confirm $^3$He Maintains Polarization for Hours Following Permeation through a Shell


- supported by the University of Virginia A&S Faculty Initiatives Research Funds
- further R&D is ongoing

- 2 mm Ø GDP pellets in a glass tube
- pellets permeated with polarized $^3$He, cooled to 77K to seal, $^3$He outside removed
- MRI time sequenced images; signal loss dominated by RF loss; polarization decay $T_1 > 6$ hours

ICF pellets can be filled with polarized $^3$He and maintained for hours at LN$_2$ (77 K)
Previous Cost/Benefit Analysis Determined SPF is a Worthwhile Development for Reactor Applications

- Analysis published in 1985:

- **Modeling setup**
  - plant costs are $\sim 1/10 \times$ ITER (STARFIRE design)
  - full polarization of injected fuel
  - no consideration for increased alpha heating
  - result: insignificant increase in reactor cost to implement SPF

- **Modest gains projected**
  - reduced cost for necessary current drive to reach ignition
  - increased lifetime of first wall
  - allows for reduced field and reactor size
  - reduced operating cost per MW
Enhanced D and T Spin Substate Populations do not Arise Naturally in a Tokamak Magnetic Equilibrium

\[ m_T = -1/2 \begin{cases} m_D = +1 \\ 2\mu_T B \end{cases} \quad m_D = 0 \quad m_D = -1 \]

\[ m_T = +1/2 \begin{cases} \mu_D B \\ 2\mu_T B \end{cases} \]

- Unequal populations → polarization
- Triton polarization: \( P(t) = N(- 1/2) - N(+ 1/2) \)
- Deuteron vector polarization: \( P^V(D) = N(- 1) - N(+ 1) \)
  - spin all parallel to B: \( P = +1 \)
  - spin all anti-parallel to B: \( P = -1 \)
- Negligible polarization from tokamak field \( \sim 10^{-9} \)

D-T Zeeman levels

\[ \mu_T = 9.4 \times 10^{-11} \text{ keV/Tesla} \]
\[ \mu_D = 2.7 \times 10^{-11} \text{ keV/Tesla} \]
Proton and alpha products from D + $^3$He reaction are lost due to their large orbit size: 14.7 MeV proton $\rightarrow$ 25 cm gyroradius at 2.15 T

Modeled scenario shows the majority of lost protons spread across a 50° poloidal range of the wall

Large SPF effect manifests as differences in fusion proton flux between anti-parallel and parallel spin alignment cases

Characteristic signature of SPF is poloidal dependence of Anti/Par proton ratio