ENN 新奥

山东大学
SHANDONG UNIVERSITY

Spin-Polarized Proton-Boron (p-^{11}B) Fusion: Pathways to Clean Energy

LI Zhi

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26th International
Symposium on Spin Physics
A Century of Spin

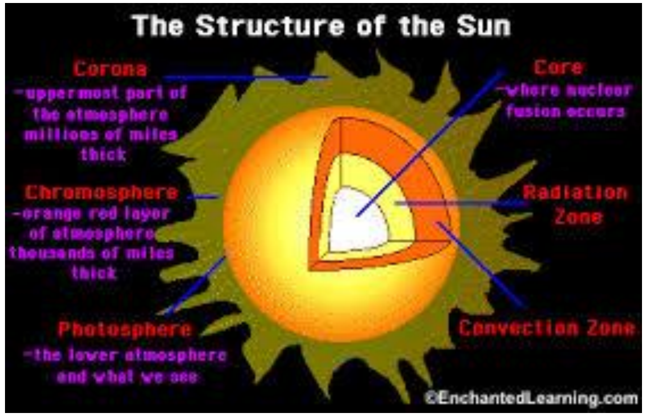
2025.09.22-26, Qingdao, China

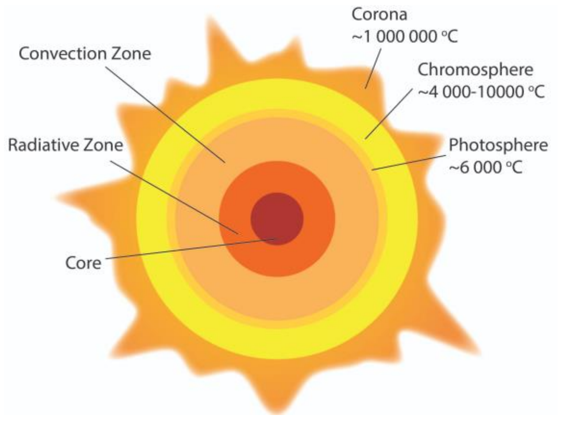
Outline

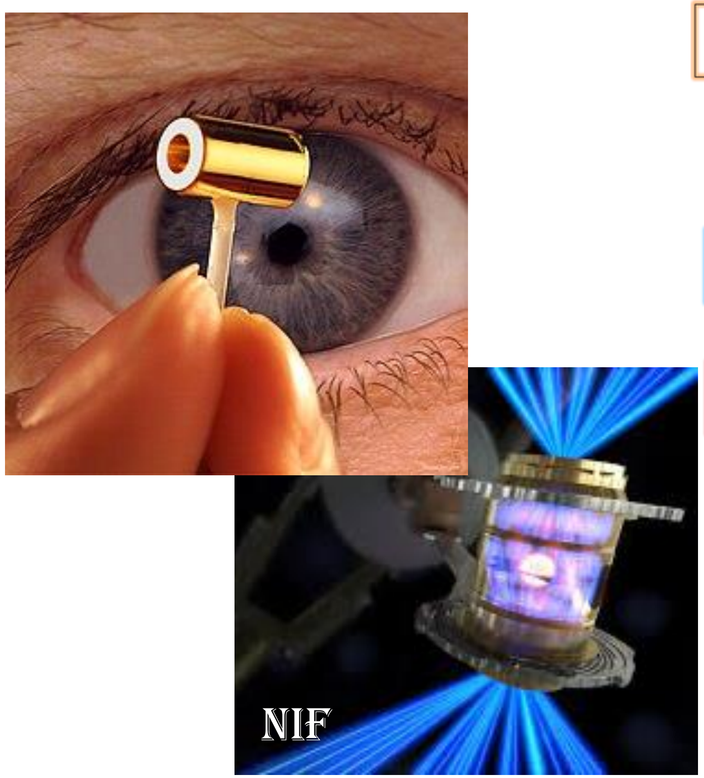
- Fusion approaches, fuel options, and critical conditions
- Ideal ignition conditions and reaction rate enhancement for p-^{11}B fusion
- Polarization research advances toward p-^{11}B fusion energy applications

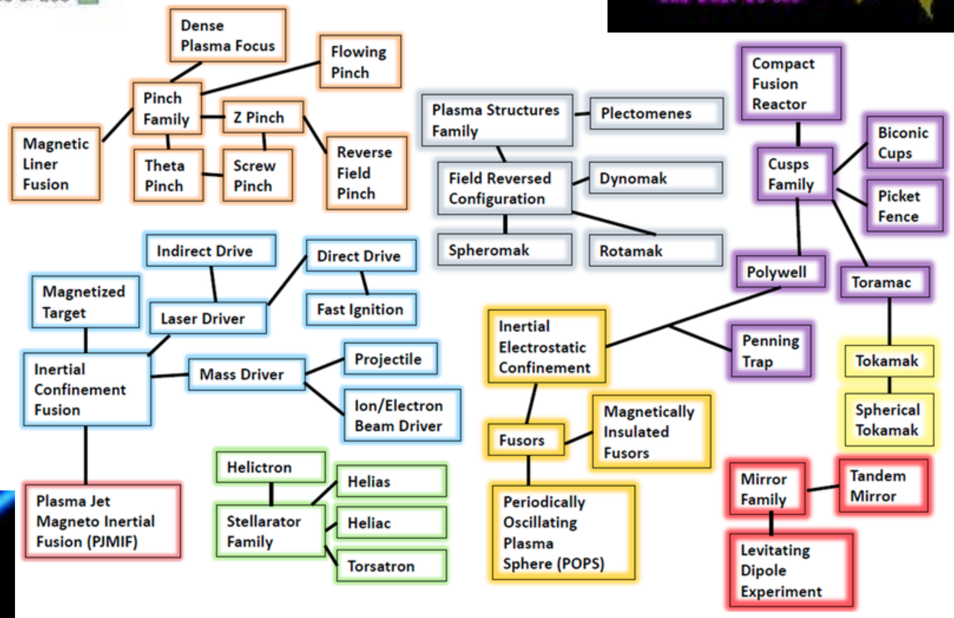
Achieved Fusion Approaches

- Hydrogen bomb
- Stars





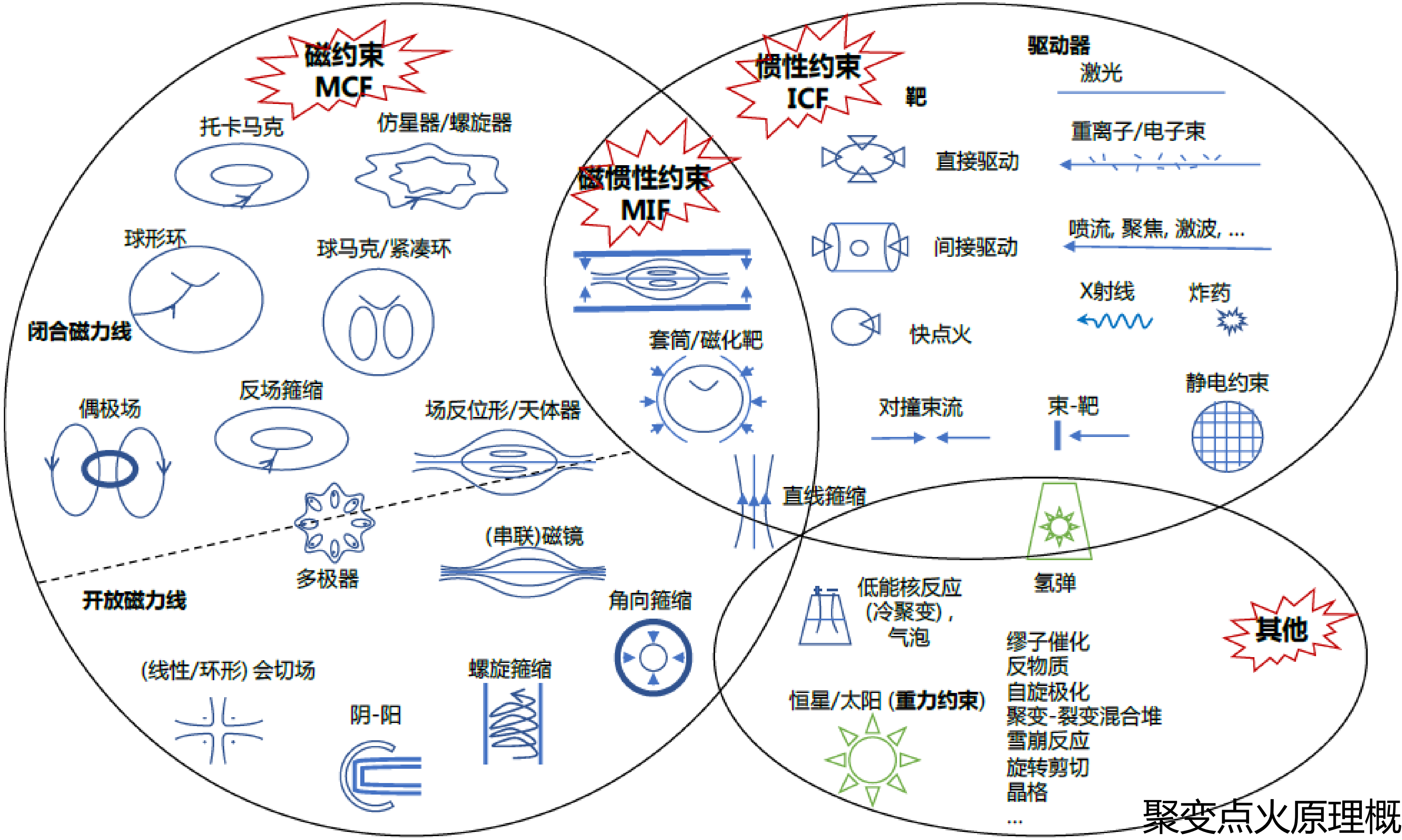




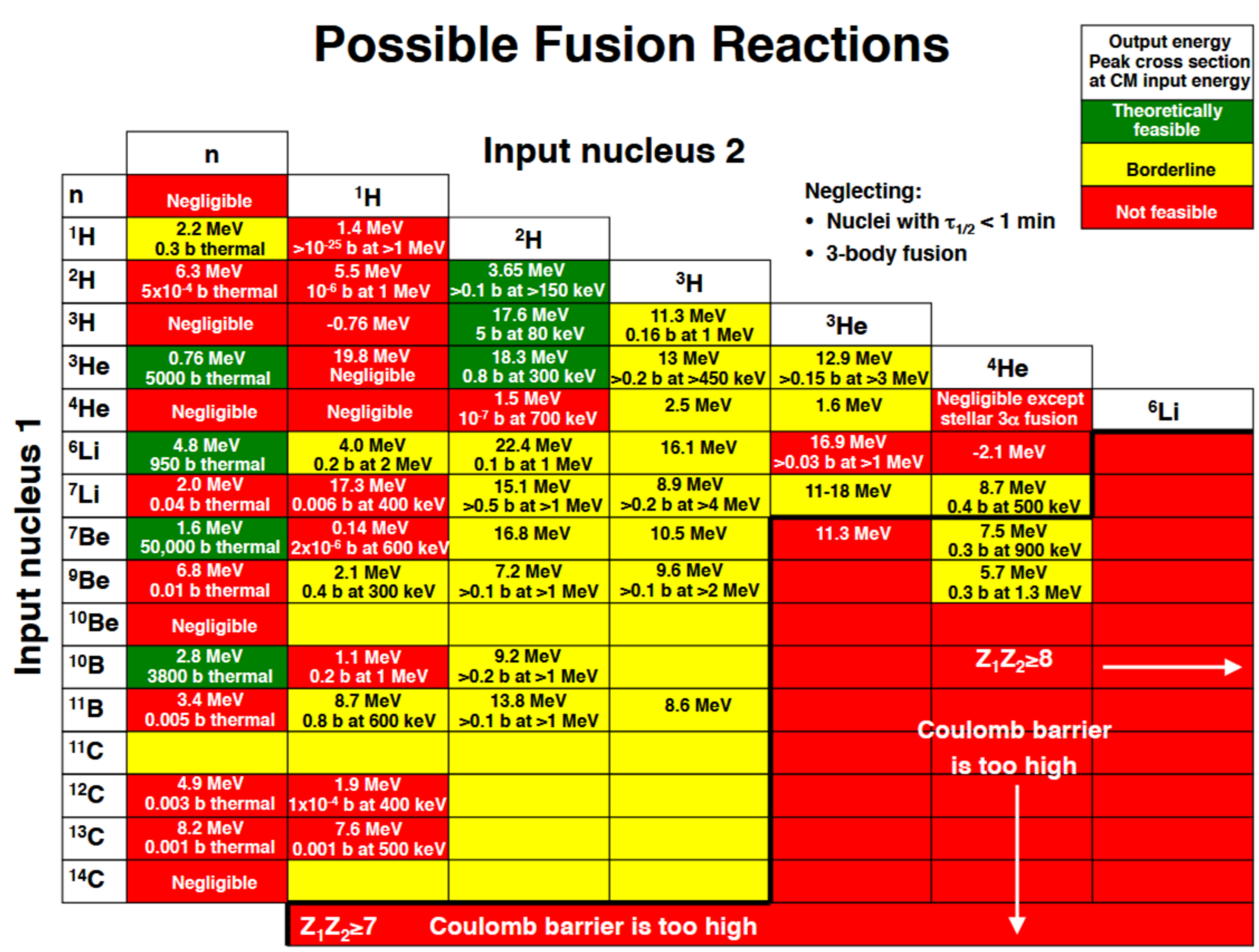
Directions for Controlled Fusion

- Inertial confinement
- Magnetic confinement

Zoo of Fusion Devices



Fusion Reactions for All Candidate Fuels



Possible Fusion Reactions

	Output energy Peak cross section at CM input energy
🟩	Theoretically feasible
🟨	Borderline
🟥	Not feasible

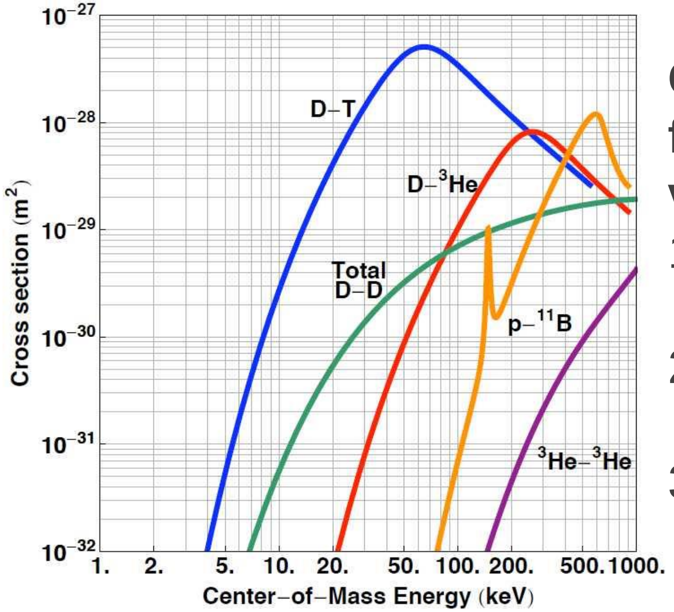
Neglecting:
- Nuclei with $\tau_{1/2} < 1$ min
- 3-body fusion

Input nucleus 2

Input nucleus 1	n	^{1}H	^{2}H	^{3}H	^{3}He	^{4}He	^{6}Li
n	Negligible						
^{1}H	2.2 MeV 0.3 b thermal	1.4 MeV $>10^{-25}$ b at >1 MeV					
^{2}H	6.3 MeV $5\text{x}10^{-4}$ b thermal	5.5 MeV 10^{-6} b at 1 MeV	3.65 MeV >0.1 b at >150 keV				
^{3}H	Negligible	-0.76 MeV	17.6 MeV 5 b at 80 keV	11.3 MeV 0.16 b at 1 MeV			
^{3}He	0.76 MeV 5000 b thermal	19.8 MeV Negligible	18.3 MeV 0.8 b at 300 keV	13 MeV >0.2 b at >450 keV	12.9 MeV >0.15 b at >3 MeV		
^{4}He	Negligible	Negligible	1.5 MeV 10^{-7} b at 700 keV	2.5 MeV	1.6 MeV	Negligible except stellar 3α fusion	
^{6}Li	4.8 MeV 950 b thermal	4.0 MeV 0.2 b at 2 MeV	22.4 MeV 0.1 b at 1 MeV	16.1 MeV	16.9 MeV >0.03 b at >1 MeV	-2.1 MeV	
^{7}Li	2.0 MeV 0.04 b thermal	17.3 MeV 0.006 b at 400 keV	15.1 MeV >0.5 b at >1 MeV	8.9 MeV >0.2 b at >4 MeV	11-18 MeV	8.7 MeV 0.4 b at 500 keV	
^{7}Be	1.6 MeV 50,000 b thermal	0.14 MeV $2\text{x}10^{-6}$ b at 600 keV	16.8 MeV	10.5 MeV	11.3 MeV	7.5 MeV 0.3 b at 900 keV	
^{9}Be	6.8 MeV 0.01 b thermal	2.1 MeV 0.4 b at 300 keV	7.2 MeV >0.1 b at >1 MeV	9.6 MeV >0.1 b at >2 MeV		5.7 MeV 0.3 b at 1.3 MeV	
^{10}Be	Negligible						
^{10}B	2.8 MeV 3800 b thermal	1.1 MeV 0.2 b at 1 MeV	9.2 MeV >0.2 b at >1 MeV			$Z_1Z_2 \geq 8$ →	
^{11}B	3.4 MeV 0.005 b thermal	8.7 MeV 0.8 b at 600 keV	13.8 MeV >0.1 b at >1 MeV	8.6 MeV		Coulomb barrier is too high ↓	
^{11}C							
^{12}C	4.9 MeV 0.003 b thermal	1.9 MeV $1\text{x}10^{-4}$ b at 400 keV					
^{13}C	8.2 MeV 0.001 b thermal	7.6 MeV 0.001 b at 500 keV					
^{14}C	Negligible						

$Z_1Z_2 \geq 7$ Coulomb barrier is too high

H. Rider. LLNL High Energy Density Science Seminar



Criteria for fusion fuel viability:

1. Reaction threshold
2. Reaction cross-section
3. Energy released

D, T, ^{3}He :

$$D + T \rightarrow n + {}^4\text{He} + 17.58\ \text{MeV}$$

$$D + {}^3\text{He} \rightarrow p + {}^4\text{He} + 18.34\ \text{MeV}$$

$$D + D \rightarrow n + {}^3\text{He} + 3.27\ \text{MeV}\ (50\%)$$

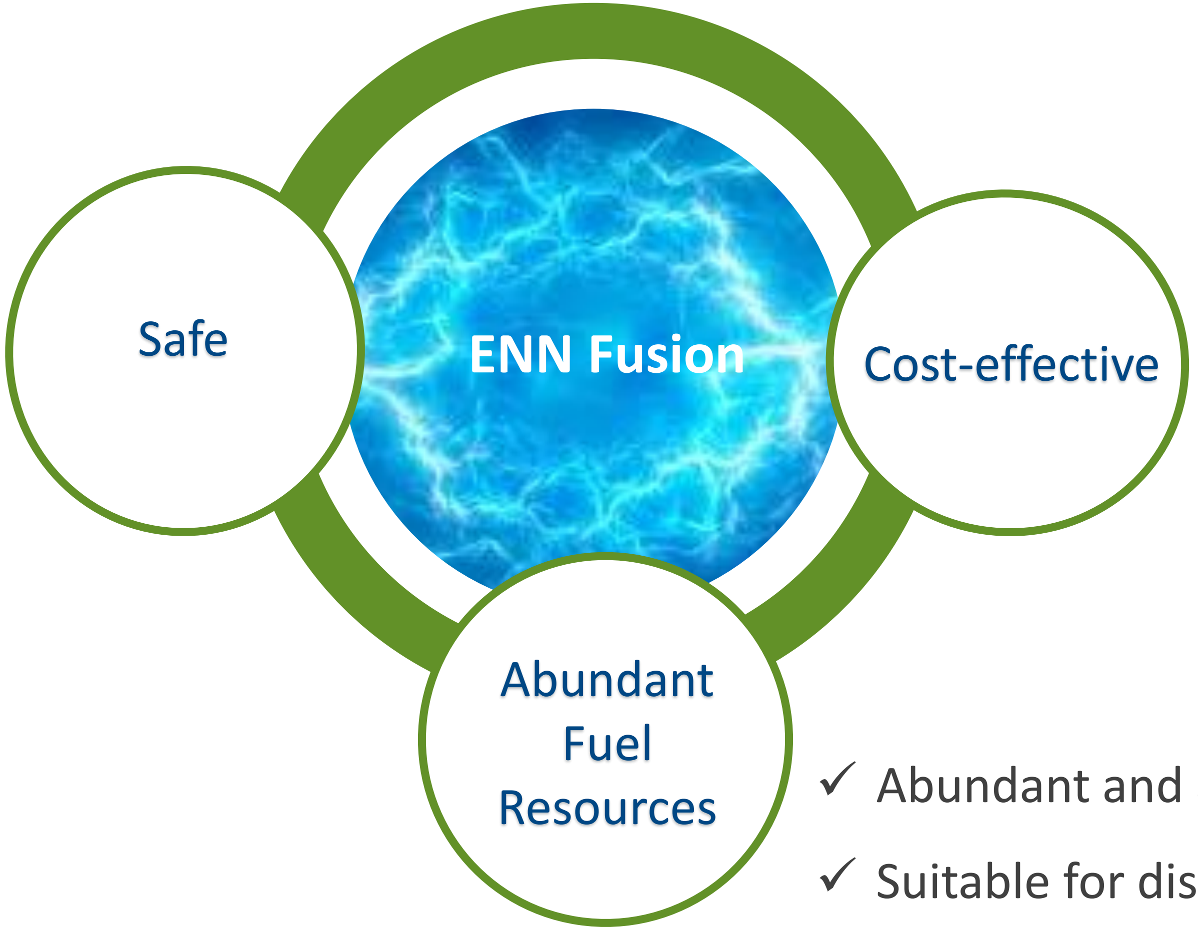
$$\rightarrow p + {}^3\text{He} + 4.03\ \text{MeV}\ (50\%)$$

✓ H, ^{11}B :

$$H + {}^{11}\text{B} \rightarrow 3\ {}^4\text{He} + 8.68\ \text{MeV}$$

Advanced fusion fuels

A Visionary Goal: Commercially Viable Fusion Power



ENN Fusion

Safe

- ✓ Aneutronic
- ✓ Pollution-free

Cost-effective

- ✓ Low-cost power generation (cheaper than wind and PV)
- ✓ Compact facility
- ✓ High energy conversion rate

Abundant Fuel Resources

- ✓ Abundant and accessible fuel
- ✓ Suitable for distributed energy market

ENN's Roadmap for p-^{11}B Fusion Power Based on the Spherical Torus (ST)

2035 **Fusion power**

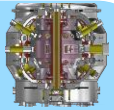
Commercial demo
2035-

- **Deliver commercially viable fusion energy at competitive cost**

p-^{11}B Burn （EHL-3A&3B）
2027-

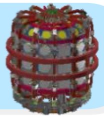
- **Achieve p-^{11}B plasma ignition and demonstrate net electricity generation**
  - ➢ Phys, engineering, tech. scale-up
  - ➢ Sustained energy gain (Q>3)

p-^{11}B Reaction (EHL-2)
2023-



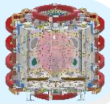
- **Validate all critical aspects of hydrogen-boron fusion**
  - ➢ Experimental verification of high-temperature plasma technologies
  - ➢ Feasibility assessment of boosted p-^{11}B fusion reaction rates

✓ **EXL-50U**
2022-



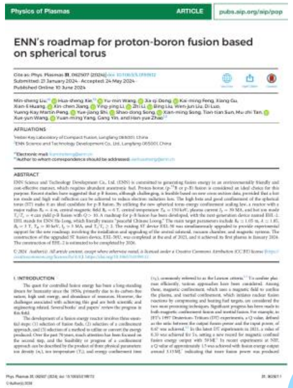
- **Develop key technologies for ST p-B fusion**
  - ➢ Enhance plasma performance parameters
  - ➢ Achieve boron fueling and robust operation control

✓ **EXL-50**
2018-2023



- **Established the basis of ST p-B fusion**
  - ➢ Initiation, ramp-up, sustainment
  - ➢ ST device design, assembly, and operation

ENN’s Roadmap for p-^{11}B Fusion Power Based on the Spherical Torus (ST)


Physics of Plasmas ARTICLE pubs.aip.org/aip/pop

ENN’s roadmap for proton-boron fusion based on spherical torus

Submitted: 21 January 2024 · Accepted: 24 May 2024 ·
Published Online: 10 June 2024

M. S. Liu, H. S. Xie, Y. M. Wang, et al., ENN’s Roadmap for Proton-Boron Fusion Based on Spherical Torus, Phys. Plasmas 31, 062507 (2024)

2035 Fusion power

Commercial demo
2035-

- **Deliver commercially viable fusion energy at competitive cost**

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2027-

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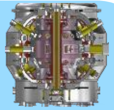

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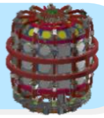
2022-



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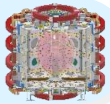
2018-2023



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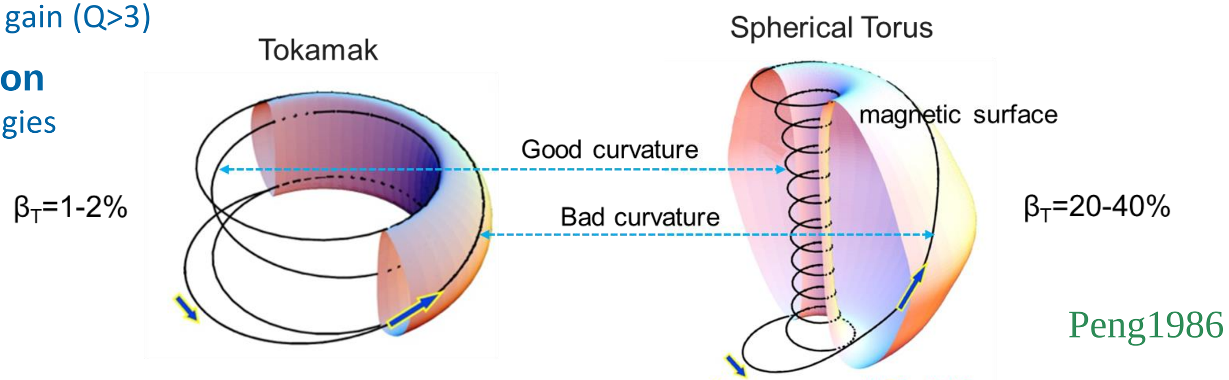
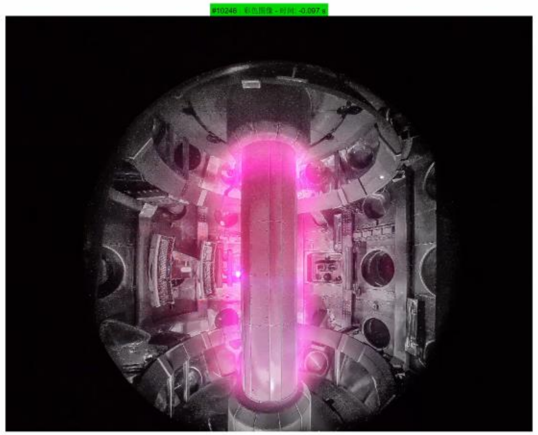
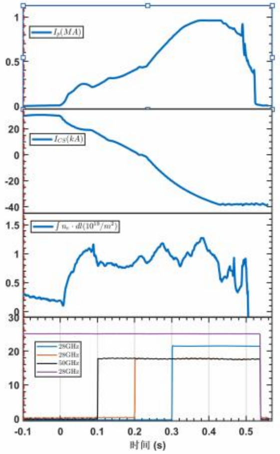
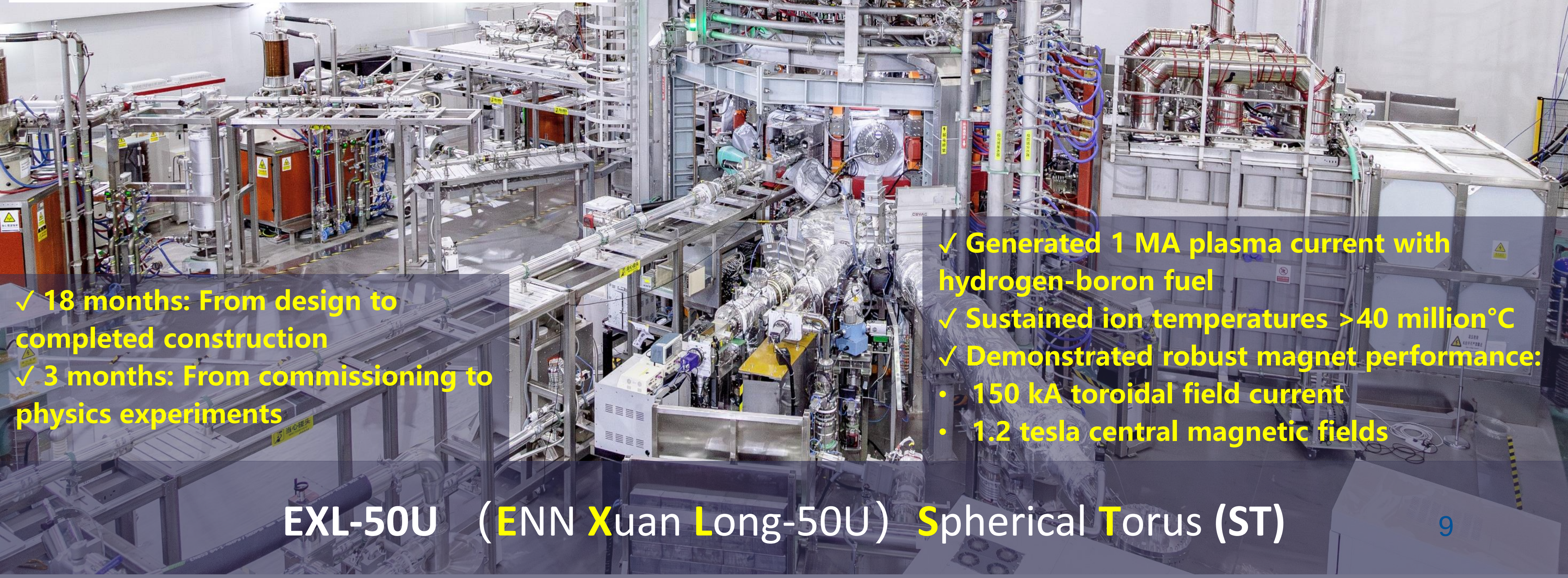


$$\tau_E^{IPB98y2} = 0.0562 I_p^{0.93} B^{0.15} P^{-0.69} n^{0.41} M^{0.19} R^{1.97} \varepsilon^{0.58} \kappa_a^{0.78} \qquad \tau_E^{ST} = 0.066 I_p^{0.53} B_T^{1.05} P^{-0.58} n^{0.65} R^{2.66} \kappa^{0.78}$$

	p-^{11}B fusion	ST
Challenge	■ Higher required triple product ■ Intense Bremsstrahlung	■ Higher β_T, lower B_T, more compact ■ t_E^{ST} leverages R and B_T, not I_P
Advantage	■ No neutron, blanket	■ More limited space for center post







✓ 18 months: From design to completed construction

✓ 3 months: From commissioning to physics experiments

✓ Generated 1 MA plasma current with hydrogen-boron fuel

✓ Sustained ion temperatures >40 million°C

✓ Demonstrated robust magnet performance:

- 150 kA toroidal field current
- 1.2 tesla central magnetic fields

EXL-50U （ENN Xuan Long-50U） Spherical Torus (ST)

Theoretical Possibility of p-^{11}B Fusion: Need for Enhanced Reaction Rates

Fusion Enhancement factor

$$Q = \frac{P_{fus}}{\frac{E_{th}}{\tau_E} - f_{ion}P_{fus} + P_{rad}}$$

$$\frac{\text{thermal energy}}{\text{energy confinement time}}$$

Fraction of fusion energy carried by charged particles

fusion power

radiation power loss

Simplified ignition criterion

$$n_e\tau_E = \frac{3}{2}k_B Z_i(1 + Z_i)(1 + \delta_{12})\frac{T}{\langle\sigma v\rangle Y_+}$$

Energy carried per reaction by charged particles.

More precise cross-section data required.

Theoretical Possibility of p-^{11}B Fusion: Need for Enhanced Reaction Rates

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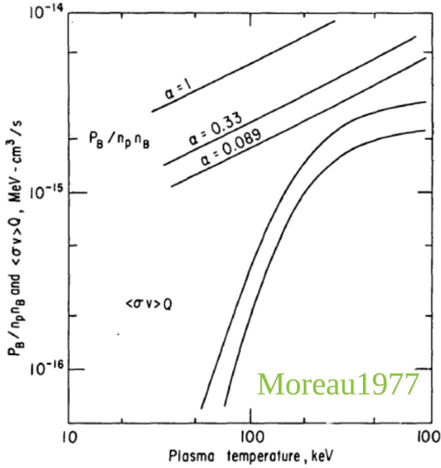
Energy carried per reaction by charged particles.

More precise cross-section data required.

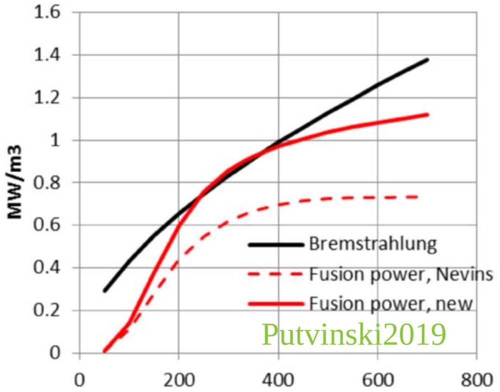
$$聚变反应率: \langle\sigma v\rangle = \int\int dv_1 dv_2 \sigma(|v_1 - v_2|)|v_1 - v_2| f_1(v_1) f_2(v_2)$$

Higher fusion reaction rate needed.

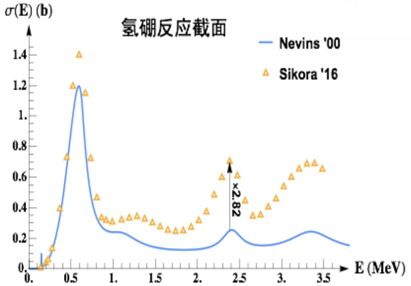


Moreau1977

p-^{11}B fusion achieves ignition with new cross-section.



Putvinski2019



Theoretical Possibility of p-^{11}B Fusion: Need for Enhanced Reaction Rates

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Energy carried per reaction by charged particles.

More precise cross-section data required.

$$\text{聚变反应率}: \langle\sigma v\rangle = \int\int dv_1 dv_2 \boxed{\sigma(|v_1-v_2|)}\boxed{|v_1-v_2|}\boxed{f_1(v_1)f_2(v_2)}$$

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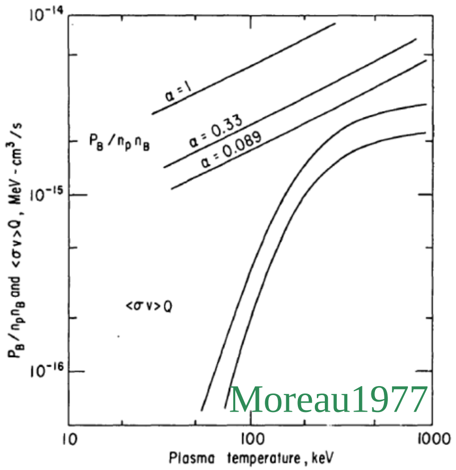
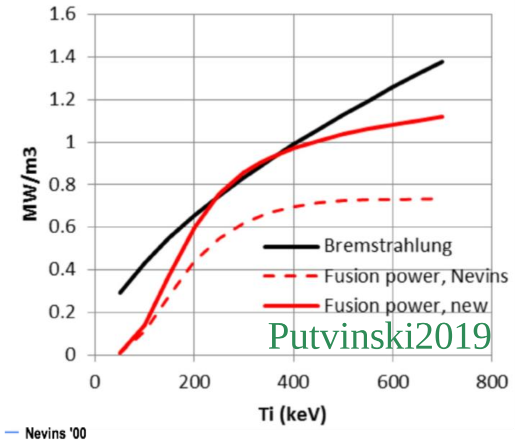
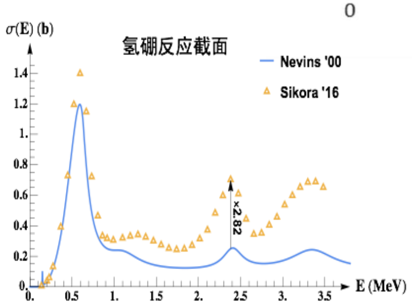
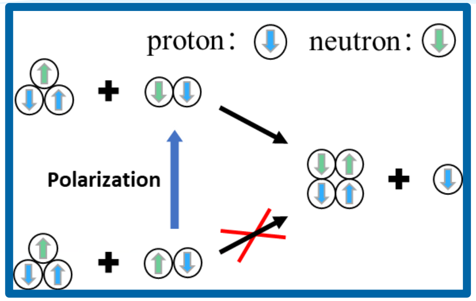


p-^{11}B fusion achieves ignition with new cross-section.

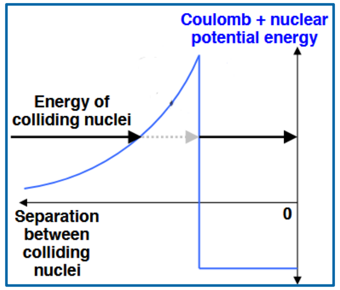




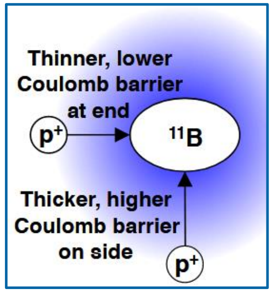
Spin-polarization



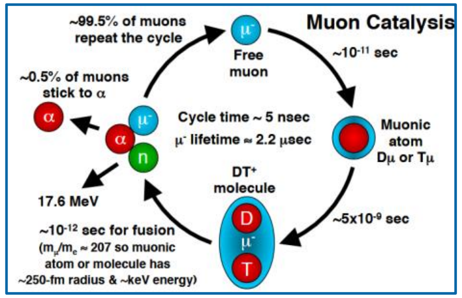
Shave Coulomb barrier



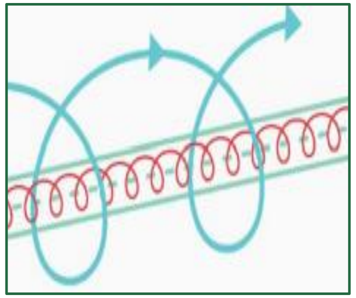
Shape-polarization



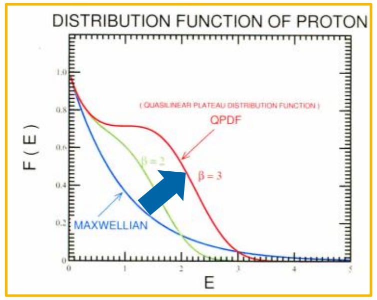
Muon Catalysis



Velocity Differential



Non-thermal



H. Rider. LLNL High Energy Density Science Seminar

Kulsrud1982, Perkins1997, Leotta1987, Wanatabe2003

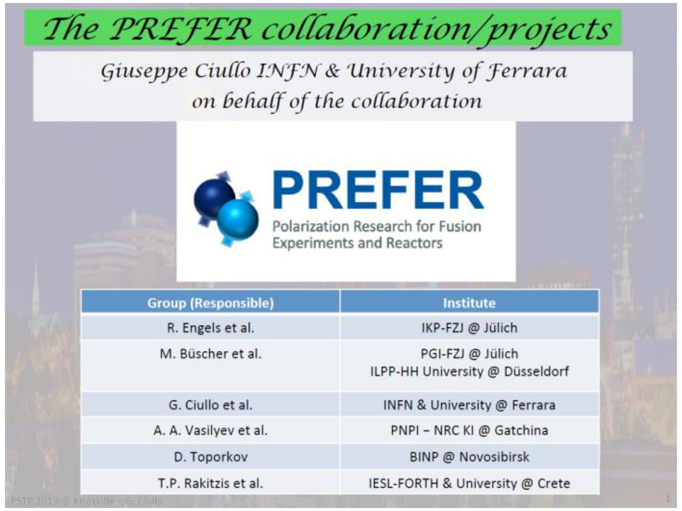
Polarization Research Advances toward Fusion Energy Applications

International research directions in polarized fusion fuels:

- Reduce T consumption in D-T fusion
- Control neutron emission direction in D-T fusion
- Enhance D-^{3}He/DD fusion performance
- Suppress neutron emission in D-^{3}He fusion

Global spin-polarized nuclear data status:

- D-D: Scarce
- D-^{3}He: Deficient
- p-^{11}B: Virtually nonexistent



The PREFER collaboration/projects

Giuseppe Ciullo INFN & University of Ferrara
on behalf of the collaboration

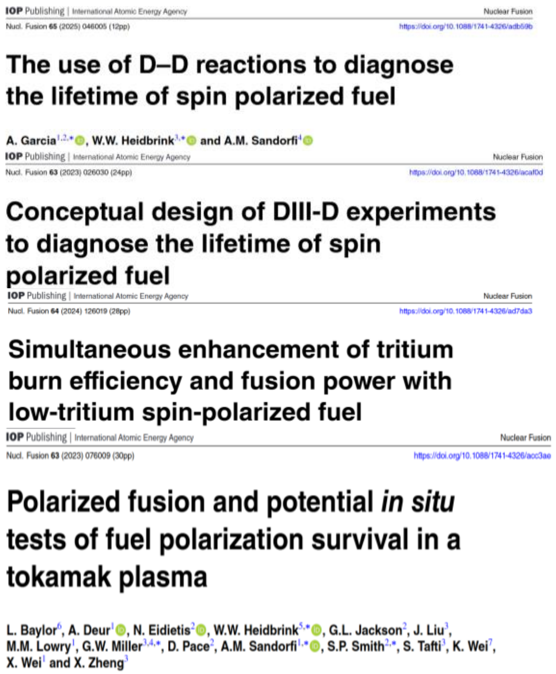
PREFER
Polarization Research for Fusion Experiments and Reactors

Group (Responsible)	Institute
R. Engels et al.	IKP-FZJ @ Jülich
M. Büscher et al.	PGI-FZJ @ Jülich ILPP-HH University @ Düsseldorf
G. Ciullo et al.	INFN & University @ Ferrara
A. A. Vasilyev et al.	PNPI – NRC KI @ Gatchina
D. Toporkov	BINP @ Novosibirsk
T.P. Rakitzis et al.	IESL-FORTH & University @ Crete

PSTP 2019 @ Knoxville – G. Ciullo

Ciullo (SPIN)

A comprehensive and systematic research plan!



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Nucl. Fusion 65 (2025) 046005 (12pp) — https://doi.org/10.1088/1741-4326/adb59b

The use of D–D reactions to diagnose the lifetime of spin polarized fuel

A. Garcia[1,2,*], W.W. Heidbrink[3,*] and A.M. Sandorfi[4]

IOP Publishing | International Atomic Energy Agency — Nuclear Fusion
Nucl. Fusion 63 (2023) 026030 (24pp) — https://doi.org/10.1088/1741-4326/acaf0d

Conceptual design of DIII-D experiments to diagnose the lifetime of spin polarized fuel

IOP Publishing | International Atomic Energy Agency — Nuclear Fusion
Nucl. Fusion 64 (2024) 126019 (28pp) — https://doi.org/10.1088/1741-4326/ad7da3

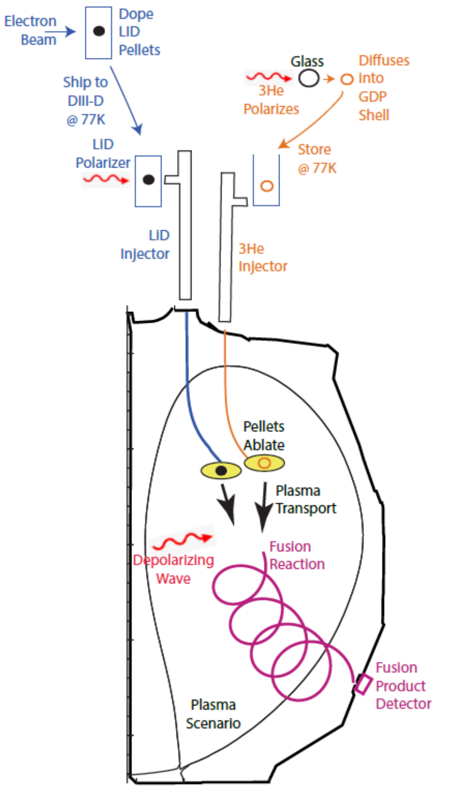
Simultaneous enhancement of tritium burn efficiency and fusion power with low-tritium spin-polarized fuel

IOP Publishing | International Atomic Energy Agency — Nuclear Fusion
Nucl. Fusion 63 (2023) 076009 (30pp) — https://doi.org/10.1088/1741-4326/acc3ae

Polarized fusion and potential *in situ* tests of fuel polarization survival in a tokamak plasma

L. Baylor[6], A. Deur[1], N. Eidietis[2], W.W. Heidbrink[5,*], G.L. Jackson[2], J. Liu[3], M.M. Lowry[1], G.W. Miller[3,4,*], D. Pace[2], A.M. Sandorfi[1,*], S.P. Smith[2,*], S. Tafti[3], K. Wei[7], X. Wei[1] and X. Zheng[3]

Lots of efforts in last 2 years!



Heidbrink (SPIN2023)

Extremely groundbreaking and brilliant research initiative!

Polarization Research Advances toward Fusion Energy Applications

International research directions in polarized fusion fuels:

- Reduce T consumption in D-T fusion
- Control neutron emission direction in D-T fusion
- Enhance D-^{3}H
- Suppress neut

Global spin-pola

- D-D: Scarce
- D-^{3}He: Deficie
- **p-^{11}B: Virtuall**


IOP Publishing | International Atomic Energy Agency Nuclear Fusion

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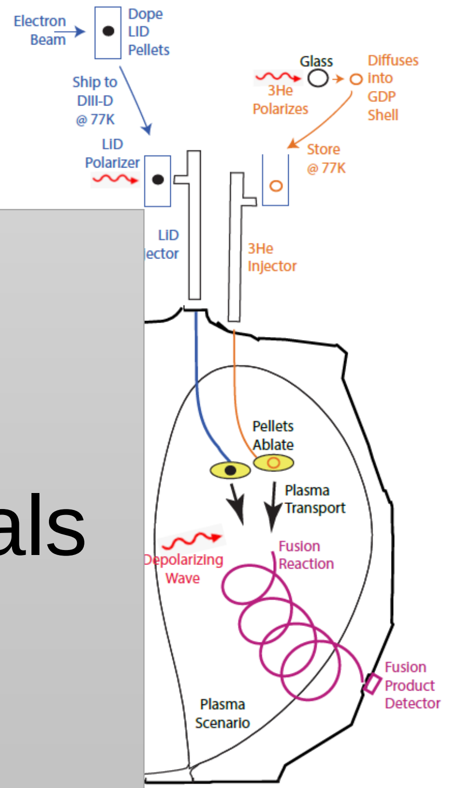
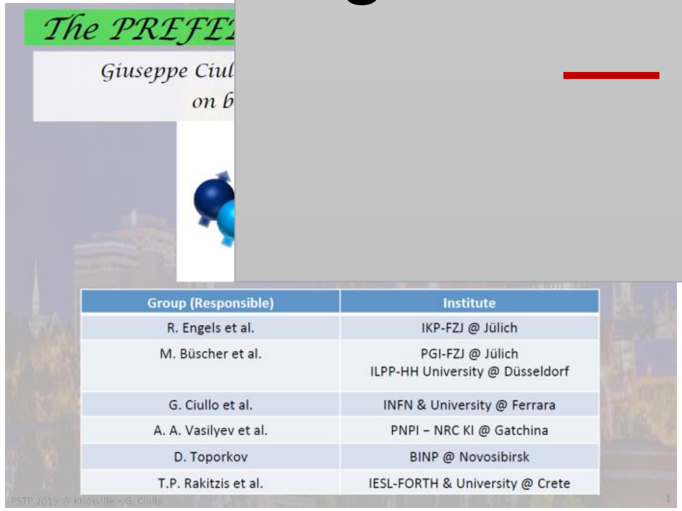


eidbrink (SPIN2023)

Numerous advantages, research agendas, and experimental proposals — yet why not p-^{11}B?


The PREFE

Giuseppe Ciul
on b

Group (Responsible)	Institute
R. Engels et al.	IKP-FZJ @ Jülich
M. Büscher et al.	PGI-FZJ @ Jülich ILPP-HH University @ Düsseldorf
G. Ciullo et al.	INFN & University @ Ferrara
A. A. Vasilyev et al.	PNPI – NRC KI @ Gatchina
D. Toporkov	BINP @ Novosibirsk
T.P. Rakitzis et al.	IESL-FORTH & University @ Crete

PSTP 2019 @ Knoxville - G. Ciullo

Ciullo (SPIN)

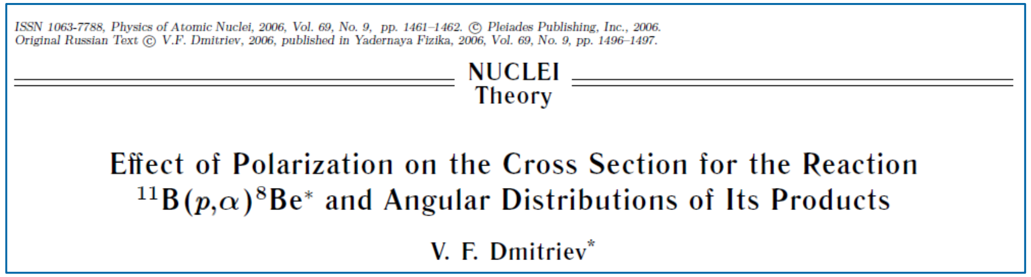
Extremely groundbreaking and brilliant research initiative!

A comprehensive and systematic research plan!

Polarization Research Advances toward p-^{11}B Fusion Energy Applications

Polarized p-^{11}B fusion research

- Remains largely unexplored
- priorities:
  - **Differential cross-section measurements of spin-polarized p-^{11}B reactions**
  - **Development of boron fuel spin-polarization techniques**
  - **Sustenance of spin-polarized hydrogen-boron plasma**

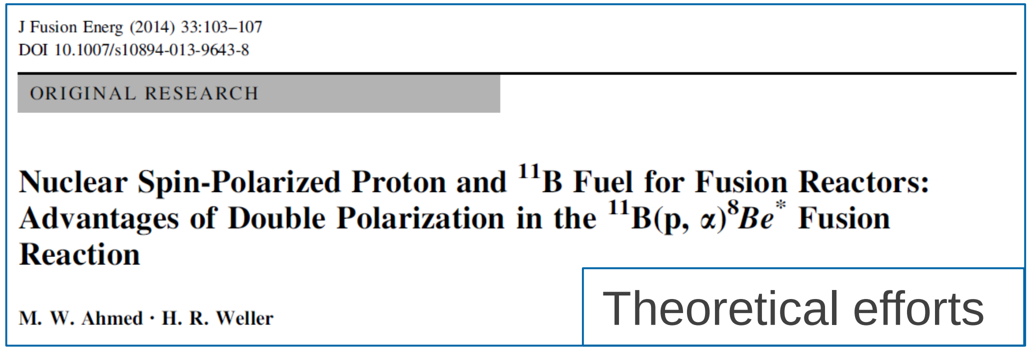


ISSN 1063-7788, Physics of Atomic Nuclei, 2006, Vol. 69, No. 9, pp. 1461–1462. © Pleiades Publishing, Inc., 2006.
Original Russian Text © V.F. Dmitriev, 2006, published in Yadernaya Fizika, 2006, Vol. 69, No. 9, pp. 1496–1497.

NUCLEI
Theory

Effect of Polarization on the Cross Section for the Reaction ^{11}B$(p,\alpha)^8$Be* and Angular Distributions of Its Products

V. F. Dmitriev*



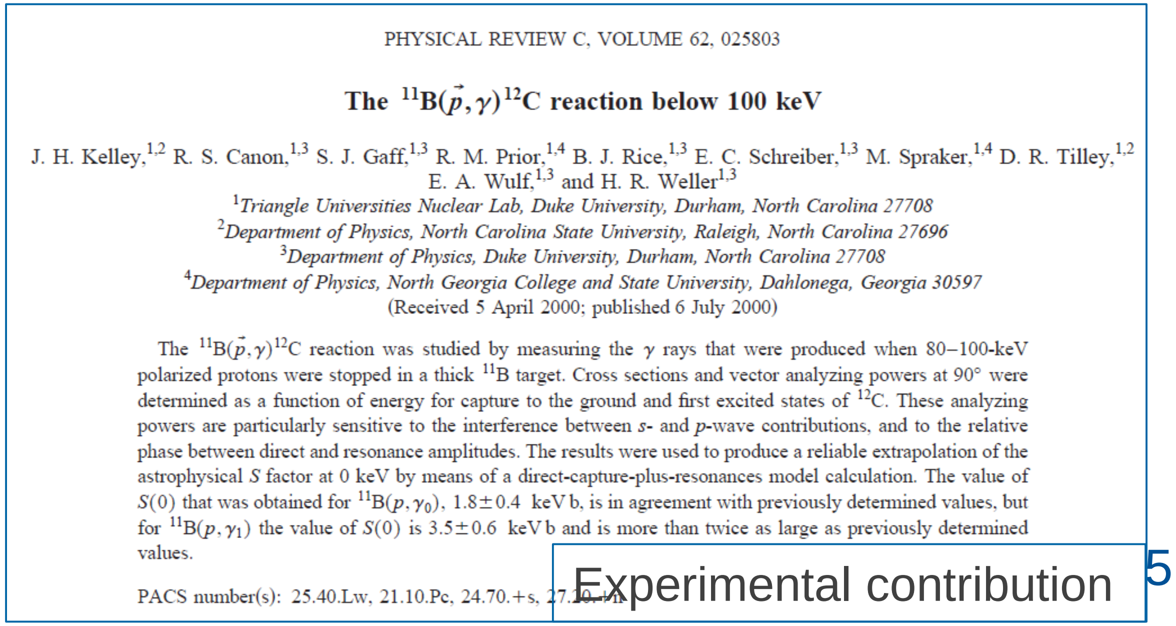
J Fusion Energ (2014) 33:103–107
DOI 10.1007/s10894-013-9643-8

ORIGINAL RESEARCH

Nuclear Spin-Polarized Proton and ^{11}B Fuel for Fusion Reactors: Advantages of Double Polarization in the ^{11}B(p, α)$^8Be^*$ Fusion Reaction

M. W. Ahmed · H. R. Weller

Theoretical efforts



PHYSICAL REVIEW C, VOLUME 62, 025803

The ^{11}B$(\vec{p},\gamma)^{12}$C reaction below 100 keV

J. H. Kelley,[1,2] R. S. Canon,[1,3] S. J. Gaff,[1,3] R. M. Prior,[1,4] B. J. Rice,[1,3] E. C. Schreiber,[1,3] M. Spraker,[1,4] D. R. Tilley,[1,2]
E. A. Wulf,[1,3] and H. R. Weller[1,3]
[1] *Triangle Universities Nuclear Lab, Duke University, Durham, North Carolina 27708*
[2] *Department of Physics, North Carolina State University, Raleigh, North Carolina 27696*
[3] *Department of Physics, Duke University, Durham, North Carolina 27708*
[4] *Department of Physics, North Georgia College and State University, Dahlonega, Georgia 30597*

(Received 5 April 2000; published 6 July 2000)

The ^{11}B$(\vec{p},\gamma)^{12}$C reaction was studied by measuring the γ rays that were produced when 80–100-keV polarized protons were stopped in a thick ^{11}B target. Cross sections and vector analyzing powers at 90° were determined as a function of energy for capture to the ground and first excited states of ^{12}C. These analyzing powers are particularly sensitive to the interference between *s*- and *p*-wave contributions, and to the relative phase between direct and resonance amplitudes. The results were used to produce a reliable extrapolation of the astrophysical S factor at 0 keV by means of a direct-capture-plus-resonances model calculation. The value of $S(0)$ that was obtained for ^{11}B(p,γ_0), 1.8 ± 0.4 keV b, is in agreement with previously determined values, but for ^{11}B(p,γ_1) the value of $S(0)$ is 3.5 ± 0.6 keV b and is more than twice as large as previously determined values.

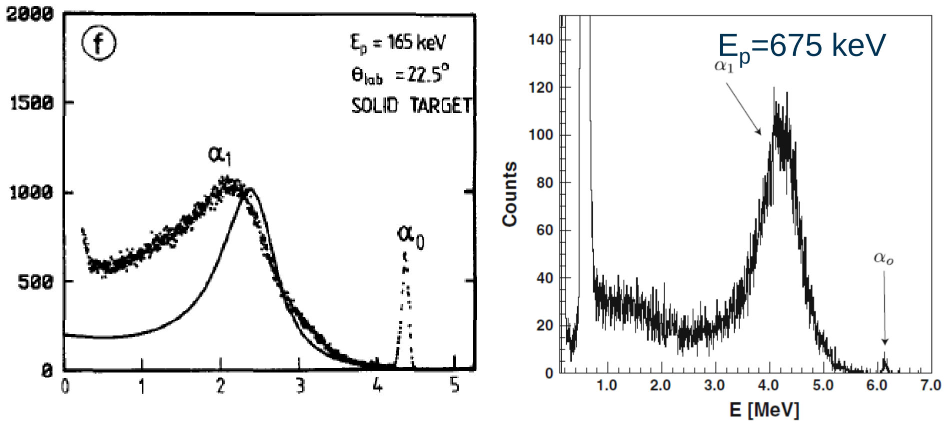
PACS number(s): 25.40.Lw, 21.10.Pc, 24.70.+s, 27.20.+n

Experimental contribution

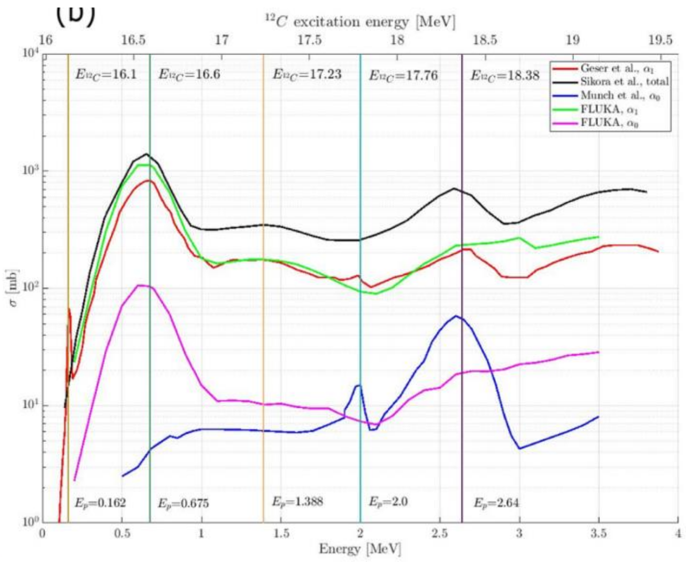
p-^{11}B Reaction: A Complex Process

Multi-pathway process with excited intermediates (^{12}C, ^{8}Be)

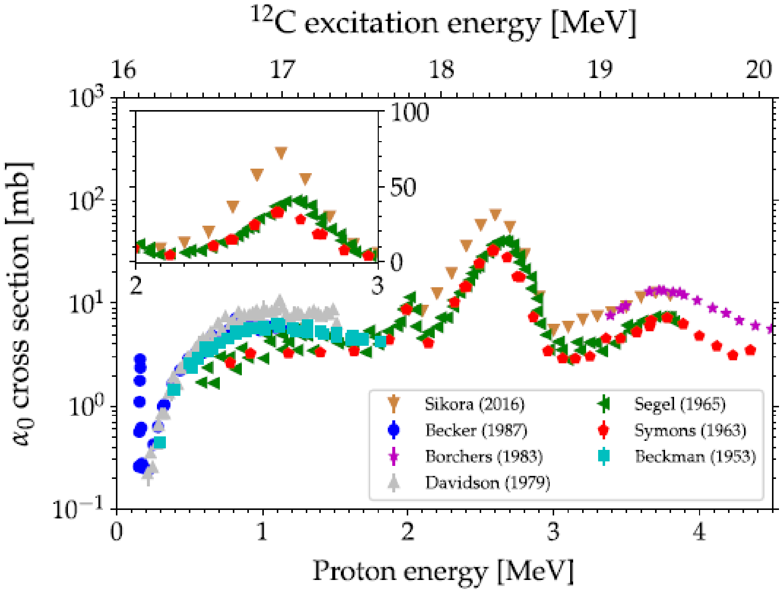
- $p+^{11}B \rightarrow ^{12}C^* \rightarrow \alpha_0+^{8}Be \rightarrow \alpha_0+\alpha_{01}+\alpha_{02}$: $^{11}\mathrm{B}(p,\alpha_0)\alpha\alpha$
- $p+^{11}B \rightarrow ^{12}C^* \rightarrow \alpha_1+^{8}Be^* \rightarrow \alpha_1+\alpha_{11}+\alpha_{12}$: $^{11}\mathrm{B}(p,\alpha_1)\alpha\alpha$
- $p+^{11}B \rightarrow ^{12}C^* \rightarrow 3\alpha$: $^{11}\mathrm{B}(p,2\alpha)\alpha$
- $p+^{11}B \rightarrow ^{12}C+\gamma_0$: $^{11}\mathrm{B}(p,\gamma_0)^{12}\mathrm{C}$
- $p+^{11}B \rightarrow ^{12}C+\gamma_1+\gamma^*$ (4.439 MeV) : $^{11}\mathrm{B}(p,\gamma_1)^{12}\mathrm{C}\gamma^*$



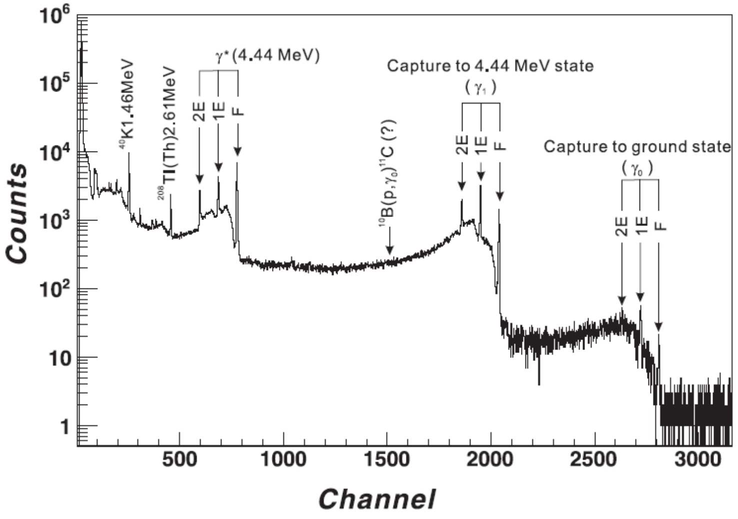
Becker1987, Spraker2012



Mazzucconi2023

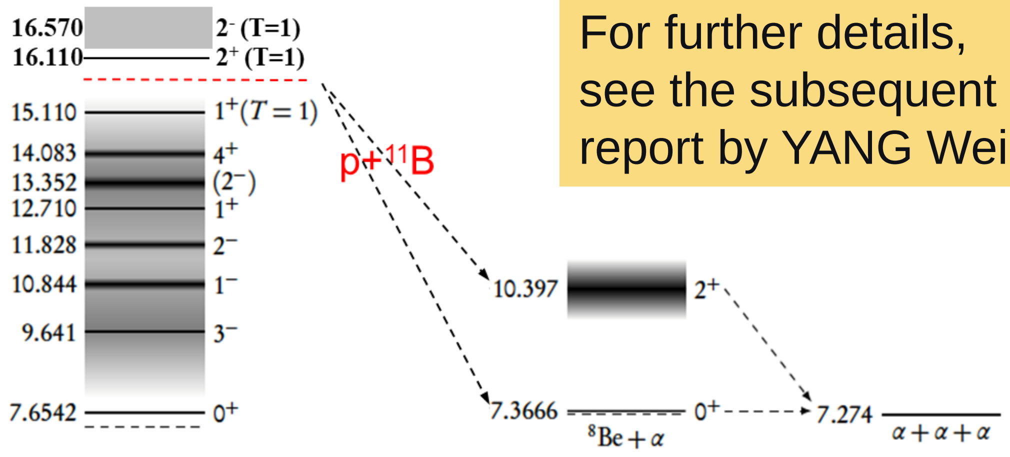


Munch2020



He2016

Key Challenges Demand Theoretical and Experimental Advances



For further details, see the subsequent report by YANG Wei

Reaction channel

Polarization resistance

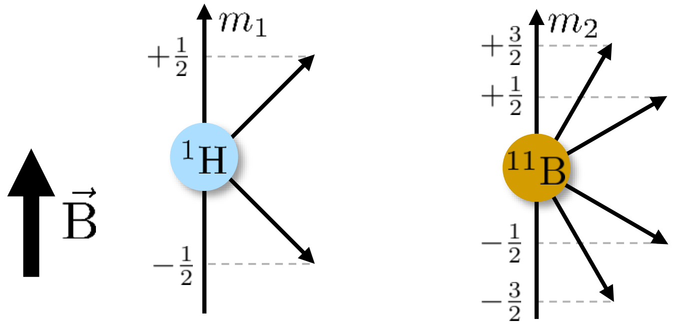
Differential Cross-Section	proton-polarized	Boron-polarized	doubly-polarized
1st resonance peat@148 keV	?	?	?
2st resonance peat@620 keV	?	?	√
Non-resonant	?	?	?

Numerous known unknowns await exploration!

❖ Polarization effects on reaction cross-section

a) Unpolarized spin $P_{m_1} = 1/2, \quad B_{m_2} = 1/4$

$$\sigma_0 = \frac{3}{8}\sigma_1 + \frac{5}{8}\sigma_2$$



b) Spin aligned along the magnetic field

i. $P_{+\frac{1}{2}} = B_{+\frac{3}{2}} = 1$

$$\sigma_{+\frac{1}{2},+\frac{3}{2}} = \sigma_2$$

ii. $P_{+\frac{1}{2}} = B_{+\frac{1}{2}} = 1$

$$\sigma_{+\frac{1}{2},+\frac{1}{2}} = \frac{1}{4}\sigma_1 + \frac{3}{4}\sigma_2$$

❖ Compared with the unpolarized scenario

$$\frac{\sigma_{+\frac{1}{2},+\frac{3}{2}}}{\sigma_0} = \frac{\sigma_2}{\frac{5}{8}\sigma_2} = \mathbf{1.6}$$

$$\frac{\sigma_{+\frac{1}{2},+\frac{1}{2}}}{\sigma_0} = \frac{\frac{3}{4}\sigma_2}{\frac{5}{8}\sigma_2} = \mathbf{1.2}$$

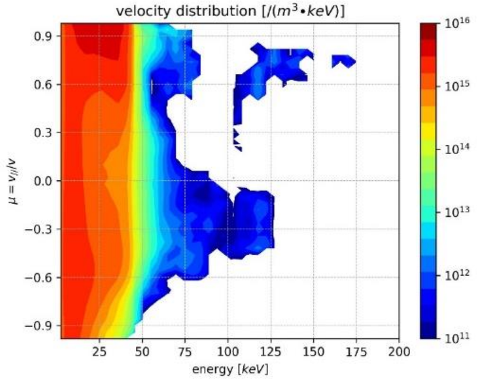
Polarized hydroboration shows **~60%** enhancement in total cross-section vs. unpolarized case

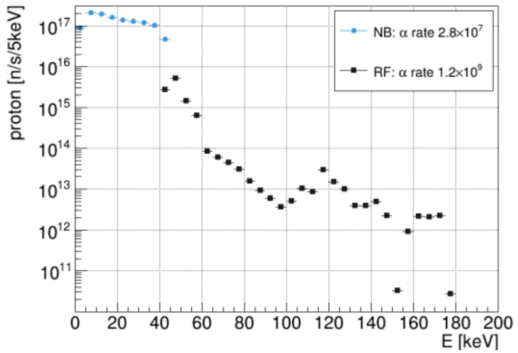
Requiring experimental verification!

Proposes for p-^{11}B polarization studies towards fusion application

Proposes for p-^{11}B fusion reaction experiments

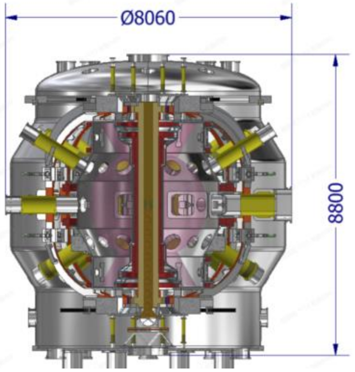
- EXL-50U (operational): experiment proposes before 2027

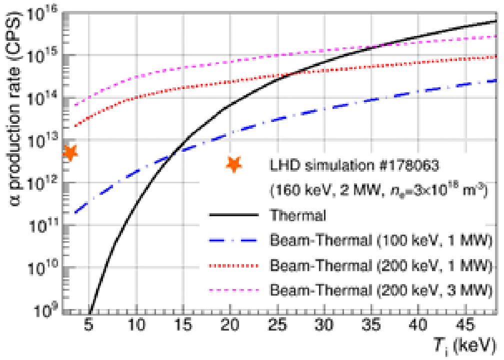




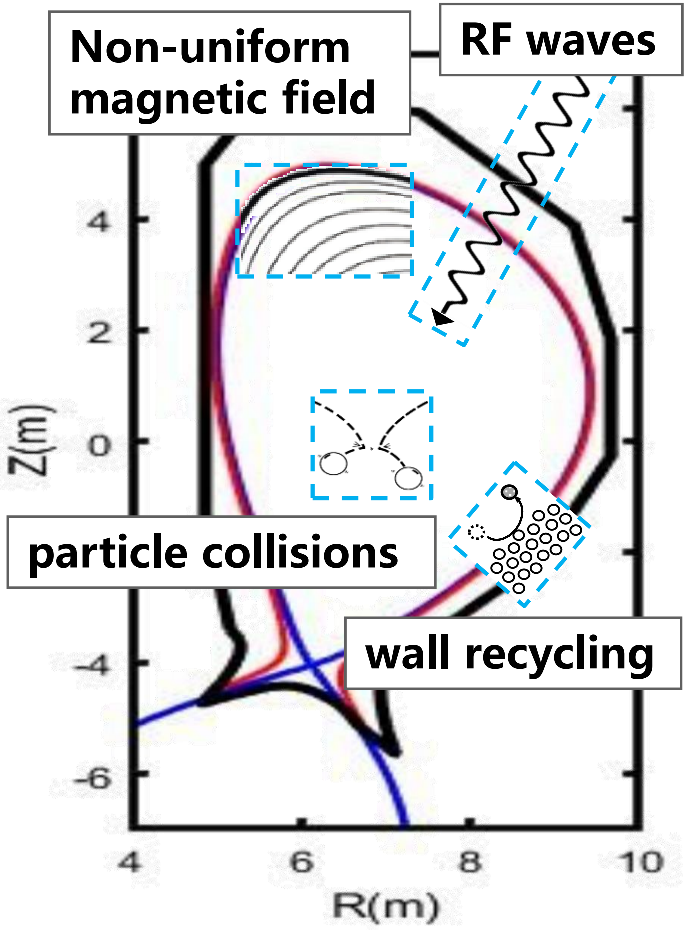
NBI-ICRF synergy-driven energetic protons initiating p-^{11}B fusion

- EHL-2 (next generation): start in 2027





Thermonuclear p-^{11}B fusion platform



Non-uniform magnetic field

RF waves

particle collisions

wall recycling

+

Spin-polarization sustainment and polarized reaction experiments?

Summary

- **proton-Boron Fusion: The Most Promising Commercialization Pathway**
- **Advantages:** Neutron-free, abundant fuel, high safety
- **Challenge:** High ignition requirements
- **Research Directions:**
  - Synergy with spherical torus configurations
  - Enhancing hydrogen-boron reaction rates
- Polarized p-^{11}B fusion research priorities:
  - **Differential cross-section measurements of spin-polarized p-^{11}B reactions**
  - **Development of boron fuel spin-polarization techniques**
  - **Sustenance of spin-polarized hydrogen-boron plasma**
- Experimental exploration on EXL-50U and EHL-2 devices
  - (Polarized) fusion reaction experiments
  - Polarized plasma generation and sustainment

Thank you for your attention!

Email：lizhiz@enn.cn

Fusion Fuel of Great Promise and Challenge: Proton-Boron

Fuel options for commercial fusion energy

Fuel	Pros	Cons	Fuel Price (USD/g)	Proven Reserves
1. D-T	Lowest ignition temp (100-200MK), high energy yield, proven scientific basis	Tritium fuel scarcity, neutron radiation challenges, nuclear waste concerns	Tritium: 30,000	25 kg
2. D-D	Abundant deuterium, no tritium needed, lower neutron yield	Higher ignition temp (400MK), lower energy yield, neutron damage	Deuterium: 4	45 trillion tons
3. D-^{3}He	Minimal neutrons, high energy yield, direct conversion	Rare ^{3}He, higher ignition temp (400MK), side reactions	^{3}He: 13700	^{3}He scarcity: Extremely rare on Earth, requiring lunar mining or D-D breeding
4. p-^{11}B	Abundant boron fuel, direct energy conversion, environmentally safe	Highest ignition temp (>1000MK), low reaction rate, S&T challenges	^{11}B: 4	1 billion metric tons

Tritium (T), helium-3 (^{3}He), and lithium-6 (^{6}Li) are government-controlled materials that are not accessible to private companies in China.