PROCEEDINGS OF SCIENCE

PREFER (Polarization for Fusion Experiments and Reactors: what is happening with regard to fusion with polarized fuel?

Giuseppe Ciullo,[a,b,*] **Markus Büscher,**[c,d] **Ralf Engels**[e,f] **and T. Peter Rakitzis**[g,h]

[a]*Dipartimento di Fisica e SdT–Università degli Studi di Ferrara, Via Saragat 1, I–44122 Ferrara, Italy.*
[b]*Istituto Nazionale di Fisica Nucleare (INFN)–sezione di Ferrara, Via Saragat 1, I–44122 Ferrara, Italy.*
[c]*Peter–Grünberg Institute (PGI–6), Forschungszentrum Jülich (FZJ), Wilhelm–Johnen–Straße, D–52428 Jülich, Germany.*
[d]*Institut für Laser– und Plasma–Physik (ILPP), Heinrich–Heine–Universität–Düsseldorf (HHUD), Universitätsstraße 1, D–40225 Düsseldorf, Germany.*
[e]*Institut für Kernphysik (IKP), Forschungszentrum Jülich (FZJ), Wilhelm–Johnen–Straße, D–52428 Jülich, Germany.*
[f]*Helmholtzzentrum für Schwerionenforschung (GSI), Planckstr. 1, D–64291 Darmstadt, Germany*
[g]*Institute of Electronic Structure and Laser (IESL) – FOundation for Reasearch and Technology – Hellas (FORTH), N. Plastira 100, GR–71110 Crete, Heraklion, Greece.*
[h]*Department of Physics, University of Crete, Voutes University Campus, GR–70013, Heraklion, Greece.*
E-mail: ciullo@fe.infn.it, Markus.Buescher@uni-duesseldorf.de, r.w.engels@fz-juelich.de, ptr@iesl.forth.gr

The **PREFER** (**P**olarization **RE**search for **F**usion **E**xperiments and **R**eactors) collaboration aims to address the know-hows in different fields and techniques to the challenging bet on energy production by nuclear fusion with polarized fuel. The collaboration involves different institutions and researchers, sharing skills and peculiar abilities, having then possibilities to span over a variety of tasks and objectives, which are under the responsibility of the authors of this contribution, leading their groups. The collaborators, each in their own activities, starting from facing open questions in the fusion reaction physics, already reach promising results, which have also acted as an inspiration and stimulus for other groups and investigations. In the following we will report in the present status of the collaboration results and working plans, opening a window on what is being moved around.

The 26th international symposium on spin physics (SPIN2025)
21–26 September, 2025
Qingdao (Tsingtao), Shandong Province, China

*Speaker

PoS(SPIN2025)170

1. Introduction

The PREFER collaboration had its first beginnings in two preliminary workshops, almost like brainstorming sessions between communities from different fields. These early beginnings are documented in a volume [1], which served as a sounding board, stimulating and drawing attention to the possibility of exploiting the potential of polarised nuclear fuel to increase the performance of nuclear fusion. The main objectives are explicitly manifested in the acronym: **P**olarisation **RE**search for **F**usion **E**xperiments and **R**eactors. The present status world wide of fusion test, project and studies, exploiting the polarization of the reactants, was presented by R. Engels [2] at this symposium with the rather explicit title of "Polarized Fusion."

In this contribution, we give more and other information, related to "what is going on", topics that have reached maturity, or are boiling in a very rich broth of ideas and skills, and which require not only the attention of researchers, but also financial support to be pursued. These topics also extend beyond the energy field of fusion, into fields of social and civil interest, as well as medical diagnostics.

Exploring the possibilities of fusion with nuclear polarized fuel involves various fields of investigation, technology, and research and development. The technology improvements in many fields during the last forty years, since the 80's when the idea of using spin–polarized fuel for fusion has been debated in literature [3], rekindled hope of pursuing the challenging task of its use for the social, climate and peaceful project of energy production from nuclear fusion. Deuterium, which is the main element for the most accessible fusion reactions, can be extracted from water which is worldwide available [4].

Promising advantages relax engineering constrains and therefore costs of fusion reactors and facilities, but some disadvantages have overshadowed the path of this research.

2. Initial challenges, restriction and expansion of collaboration

The possibility of using nuclear polarized fuel, involving reacting nuclei, having spin 1/2 (T, ^{3}He) and spin 1 (D), covering the first three reaction generations, sorted by the relative energy, or by the temperature of the fusion plasma, has been established in theoretical models [5, 6] and experimentally confirmed for spin 1/2–spin 1 reacting nuclei [7].

Cross–section measurements, in scattering experiments, yield several advantages, described in detail by R. Engels [2], which we summarize and synthesize as *increasing the cross–section* and *controlling the angular distribution* of the reaction products.

Such advantages, in various studies and predictions, would lead to performance improvements in fusion facilities, as well documented in the aforementioned presentation [2].

The challenges, facing the PREFER collaboration, include the *production of polarized fuel*, its *survival in fusion environments*, and its manipulation in and for such environments.

While we obtain such advantages for the reactions of spin 1/2–spin 1 reactants, verified in scattering experiments [7], unlikely for the spin 1–spin 1 reactants we are practically blind [5].

We lack sufficient data to constrain the available mathematical models, to the point that the theoretically simplest cross–section between both vector polarized deuterium reactants also disrupts nuclear physics for four–body interactions and astrophysics dilemma, due to the Quinted Suppression

Factor (QSF) crisis, where various nuclear models provide predictions ranging from 2.5 to 0 at the energy of interest for fusion [8].

The initial challenges involved leveraging the expertise, acquired within the community active in the production of polarized nuclear targets for the study of fundamental subnuclear physics: the bottleneck of these challenges was, and still is, the ability to produce and manipulate highly polarized and highly dense fuel, but also any effort will be useless if the polarization cannot survive in fusion environments. At its inception, the collaboration was a connection between various groups.

A group, led by M. Büscher (University of Düsserldorf and FZ–Jülich) which has expertise in induced plasma acceleration and aims to study survival of the nuclear polarization in laser environments comparable to those of inertial confinement fusion [9–14].

A group led by R. Engels (IKP–FZJ–Jülich), which has expertise in the production of polarized atomic beams, their diagnostics, and recombination to obtain hyper–polarized molecules [15–18].

A group, led by D. Toporkov (BINP–Novosibirsk), which is active in the separation of hyperpolarized molecules using the Stern–Gerlach separation technique, with the use of superconducting magnetic hexapoles [19, 20].

A group, led by A. Vasilyev (PNPI–Gatchina), which has expertise in the cryogenics, atomic beams sources and nuclear detection techniques, where the collaboration supported and maintained the facility for measurements of the spin-dependent D–D reactions [21, 22].

A group, led by G. Ciullo (University and INFN–Ferrara), which has expertise in polarized atomic beams and high-temperature superconducting systems, useful as containment fields for the transport and manipulation of polarized substances [23, 24].

After 2022, Russian institutes were not allowed to continue their cooperation.

But in the meantime the collaboration has also seen his area of interest expanded in a group, led by T. P. Razitkis (University and IESL-FORTH, Crete), which brought in the collaboration more contributions in proposing solutions and technologies [25–29]. These contributions should satisfy the intensity and degree of polarization for fusion purposes, but also extend the polarization in branches of chemistry for studies of climatic interest, and in branches of medical diagnostics.

3. Results achieved to date and proposals in progress

A result achieved by the PREFER collaboration has undoubtedly been the opportunity to highlight a potential keystone for the use of fusion for energy production among various researchers [1]. From the beginning the collaboration organized annual workshops until 2019, at the various locations of the aforementioned groups. Thanks to the growing interest on the topic from 2018 they have been parallel sessions of contributions at the biennial SPIN symposia and plenary contributions at the biennial PSTP workshops. The first test on polarized 3He and D under studies on the DIII-D tokamak, was born and discussed in the meeting of the spin- community [30].

In 2024 a very focused and specialized workshop, organized in Washington by the ARPA-E agency of the Department of Energy, was devoted to take stock of the state of fusion with polarized fuel, and to invest in mature technologies for their use in electricity generation [31].

The boost on the topics of these efforts can be seen in recent publications on projects for the exploitation of polarized fuel in various fields of nuclear fusion [32–34].

The group led by M. Büscher, in synergy with other groups, achieved decisive results in the acceleration of polarized ions [14], for hydrogen [10, 11], polarized ^{3}He [12], and electrons and in polarimetry in hostile environments as in high power laser [10–12]. The evidence of survival of the polarization is a milestone for taking its advantages in fusion programs [13].

The group led by R. Engels achieved decisive results in the production and diagnostics of hyper–polarized molecules [15–18], and proposed a method of polarization technique, which can be extended also to molecules for the production of intense and highly polarized molecular beams [29].

The group, led by A. Vasilyev, although no longer part of the collaboration from 2022, has published works, demonstrating the facility availability for measuring spin–dependent cross–sections for the D–D reactions in the energy range of interest for nuclear fusion and astrophysics, which should provide the required data for the solution of the QSF dilemma [22].

The Novosibirsk group provided a lower limit on how many polarized molecules can be produced using the Stern-Gerlach technique, but only because, due to the inability to join the PREFER collaboration, they did not continue their experimental work on tests that would have increased the intensity [20].

The Ferrara group achieved decisive results in the possibility of using superconducting systems for the manipulation and transport of polarized substances, having designed and commissioned a facility for their characterization [24]. Useful systems for the purpose are already available [35].

The Crete group provided innovative advances of several orders of magnitude and, therefore, superior to what is currently available for the production of hydrogen isotopes and polarized electrons [25, 26]. The available laser techniques may contribute to the hyperpolarization of molecules for their non-invasive use, even in medical diagnostics [27].

4. The new frontiers for the nuclear polarization and the contribution from the PREFER collaboration

Nowadays polarized atomic beams reach intensities of 10^{17} atoms s^{-1} and high polarization values up to P$\sim$0.9, e.g. for polarized nuclear target at several accelerators.

The ability to recombine polarized atoms and preserve the nuclear polarization has been demonstrated for H_2, D_2 and HD [15, 17]. The possibility to condense the molecules and transport them in fusion facilities is also in the hands of the collaboration [24]. But the density of the polarized substances is about seven order of magnitude less compared to the requirement for fusion facilities. Nevertheless, it would be useful for tests on preservation of polarization, in order to get the missing data for polarized fuel reaction, but still not enough for feeding tokamaks [30].

The boost to the production come from ideas and tests, born under the umbrella of the collaboration and thanks to activities carried out in synergy between the different groups, and can be distinguished in the following topics:

A: spin manipulation by static magnetic fields.

B: spin–polarized atoms from molecular dissociation.

C: large production rates of spin–polarized molecules from infra–red–excitation of molecular beams.

4.1 A: spin manipulation by static magnetic fields.

Recently, the collaboration has been researching a promising technique that utilizes induced coherent transitions between quantum states with very small energy differences [18]. The technique is used in several variations in different experiments to flip the nuclear spin and is known under different names such as Majorana–, non–adiabatic–, diabatic–, Sona–, or spin–flip–transitions.

In a recent paper a versatile theoretical and computational framework for analyzing the spin dynamics of particle beams with interacting angular momenta in, generally speaking, static, spatially varying magnetic fields has been published [29]. The framework has been deeply discussed for H, D and also for HD molecules: this technique allows to boost the polarization for its use in nuclear fusion.

4.2 B: spin–polarized atoms from molecular dissociation.

The Rakitzis group showed that the photo–dissociation of hydrogen halide molecules (HX) with circularly polarized UV light produces Spin–Polarized Hydrogen (SPH). By photo–dissociation of HCl, HBr and DI it was shown that ultra–high density spin–polarized H (SPH) and D (SPD) atoms can be generated: the way is open to generate very intense polarized proton and deuteron beams by subsequent selective ionization [25]. The expected density is at least of the order of 10^{19} cm^{-3}, which is very promising for fusion research or for polarized ion beams in accelerator physics [26], compared to density of 10^{12} cm^{-3} from polarized atomic beams.

The collaboration between the aforementioned groups with their respective tools and knowledge will lead to fruitful results in the exploitation of this new ultra–high density regime of spin–polarized H and D atoms.

4.3 C: large production rates of spin–polarized molecules from infra–red excitation of molecular beams.

The Rakitzis group also proposed to polarize molecules through the ro–vibrational excitation of molecules beams with circularly polarized pulsed Infra–Red (IR) lasers. The IR excitation polarizes the molecular rotation, and its polarization is transferred to the nuclear spins through the hyperfine interaction.

Recently, Kannis and Rakitzis have extended the IR–excitation proposals for the direct polarization of HD, or DT, molecular beams [28].

Predictions are estimated for production in the order of 10^{20} hyper–polarized molecules s^{-1}, thanks to the availability of lasers that produce 10^{21} IR photons s^{-1} [27], that is impressive if compared to the intensity of 10^{17} polarized atoms/s^{-1}.

The possibility of using a freezing surface in a magnetic field inside a MgB_2 cylinder without a power supply opens the door to transport the polarized substances for further tests in fusion facilities [23]. A dedicated apparatus for testing the superconducting MgB_2 material was put into operation in Ferrara [24]. Several hollow MgB_2 cylinders, produced using the so–called Reactive Liquid Infiltration (RLI) technique [35], have been shown to be useful, demonstrating that there are viable products for this purpose that are capable of conserving a magnetic field of 960 mT when cooled below its critical temperature (39 K) in an external magnetic field of 970 mT.

The production and manipulation of spin–polarized electrons and nuclei are fundamental to many fields, but the current methods of production of hyper–polarized fuel have significant limitations in production rates and polarization. The requirement for fusion of at least 10^{21} polarized nuclei/s is too high for the present production of 10^{17} polarized atoms/s by polarized atomic beam sources. There are evidence of polarization survival in some fusion test tests with laser–induced plasmas and corresponding investigations for magnetic confinement fusion in tokamaks is foreseen in near future. This efforts can be very fruitful for fusion energy production, if we can reach the requirements in intensity and polarization of the fuel.

5. Acknowledgments

The work is partially supported by the German Deusche Forschungsgemeinschaft (grant no, BU 2227/1 – 1) and the Italian “Progetto Strategico" INFN-Energia.

References

[1] G. Ciullo *et al.* (Ed.s), *Nuclear Fusion with Polarized Fuel*, Springer Proc. in Physics **187** (2016).

[2] R. Engels, *Polarized Fusion* in this Symposium.

[3] R. M. Kulsrud *et al.*, *Fusion Reactor Plasmas with Polarized Nuclei*, Phys. Rev. Lett. **49** (1982) 1248.

[4] P. K. Kaw and I. Bandyopadhyay, *The case for fusion* in *Fusion Physics*, M. Kikuchi, K. Lackner and M. Q. Tran (Ed.s), International Atomic Energy Agency, 2012, Vienna.

[5] H. Paetz gen. Schieck, *Spin Physics and Polarized Fusion: Where We Stand*, in *Nuclear Fusion with Polarized Fuel*, Springer Proc. in Physics **187** (2016) 15.

[6] G. Hupin *et al.*, *Ab initio prediction for deuterium–tritium fusion reaction*, Nat. Comm. **10** (2019) 351.

[7] Ch. Leemann *et al.*, *Investigation of the* $^3\overrightarrow{He}(\overrightarrow{\mathrm{d}}, p)^4He$ *Reaction with Polarized Beam and Target at 430 keV*, Ann. Phys. **66** (1971) 810.

[8] M. Viviani *et al.*, *Theoretical study of the* $d(d, p)^3H$ *and* $d(d, n)^3He$ *process at low energies*, Phys. Rev. Lett. **130** (2023) 122501.

[9] I. Engin *et al.*, *Laser–induced acceleration of Helium ions from unpolarized gas jets*, Plasm. Phys. Contr. Fus. **61** (2019) 115012.

[10] Hützen *et al.*, *Polarized proton beams from laser–induced plasmas*, High Pow. Las. Sci. Eng. **7** (2019) e16.

[11] X. F. Li, *et al.*, *Polarized proton acceleration in ultra intense laser interaction with near–critical–density plasmas*, Phys. Rev. E **104** (2021) 015216.

[12] P. Fedorets, *et al.*, *A High-Density Polarized ^{3}He Gas–Jet Target for Laser–Plasma Applications*, Instruments **6** (2022) 18.

[13] C. Zheng *et al.*, *Preservation of ^{3}He ion polarization after laser-plasma acceleration* [e-Print: arXiv:2310.04184 [physics.plasm-ph]]

[14] L. Reichwein *et al.*, *Plasma acceleration of polarized particle beams*, Rep. Prog. Phys. **88** (2025) 117001.

[15] R. Engels *et al.*, *Production of Hyper–polarized H_2 Molecules from $\overrightarrow{H}$ Atoms in Gas–Storage Cells*, Phys. Rev. Lett. **115** (2015) 113007.

[16] L. Huxold *et al.*, *A Lamb-Shift Polarimeter for $\overrightarrow{H}$ and $\overrightarrow{D}$ Molecules*, in *23*rd*International Spin Physics Symposium Spin2018*, Proc. of Science **346** (2019) 105.

[17] R. Engels *et al.*, *Production of HD Molecules in Definite Hyperfine Substates*, Phys. Rev. Lett. **124** (2020) 113003.

[18] R. Engels *et al.*, *Direct observation of transitions between quantum states with energy differences below 10 neV employing a Sona unit*, Eur. Phys. J. D **124** (2021) 25.

[19] D. K. Toporkov *et al.*, *An Experimental Setup for Production of Polarized H_2 and D_2 molecules*, Instrum. Exper. Techn. **92** (2019) 56-61.

[20] Yu. V. Shestakov *et al.*, *Nuclear–Polarized Hydrogen/Deuterium Molecular Source*, Phys. Part. Nucl. **50** (2019) 513.

[21] A. Solovev *et al.*, *Optimization and first tests of the experimental setup to investigate the double-polarized DD-fusion reactions*, J. Instrum. **15** (2020) C08003.

[22] A. Yu. Rozhdestvenskij *et al.*, *Project on Research of Nuclear dd Synthesis with Polarization of Initial Particles at Low Energies (PolFusion)*, Phys. Atom. Nucl. **87** (2024) 24.

[23] M. Statera *et al.*, *A bulk superconducting MgB_2 cylinder for holding transversely polarized targets*, Nucl. Instr. Meth. A **882** (2018) 17.

[24] G. Ciullo *et al.*, *Bulk superconducting materials as a tool for control, confinement, and accumulation of polarized substances: the case of MgB_2*, Front. Phys. **12** (2024) 1358369.

[25] D. Sofikitis *et al.*, *Photofragment spin–polarization measurements: via magnetization quantum beats: dynamics of DI photodissociation*, Phys. Chem. Chem. Phys. **21** (2019) 14000.

[26] A. Spiliotis *et al.*, *Ultrahigh–density spin–polarized hydrogen isotopes from the photodissociation of hydrogen halides: new applications for laser–ion acceleration, magnetometry, and polarized nuclear fusion*, Light Sc. Appl. **10** (2021)35.

[27] C. S. Kannis and T. P. Rakitzis, *Macroscopic production of highly nuclear–spin–polarized molecules from IR–excitation and photodissociation of molecular beams*, Chem. Phys. Lett. **784** (2021)139092.

[28] C. S. Kannis and T. P. Rakitzis *Production of Spin-Polarized Molecular Beams via Microwave or Infrared Rotational Excitation*, [e-Print: arXiv:2503.08435v2].

[29] C. S. Kannis *et al.*, *Spin manipulation and nuclear polarization enhancement in particle beams with static magnetic fields*, Phis. Rev. A **112** (2025) 012801.

[30] W. W. Heidbrink *et al.*, *A reaserch program to measure the lifetime of spin polarized fuel*, Front. Phys. **12** (2024) 1355212.

[31] Spin Polarized Fusion (SPF) Workshop, Dec 09 2024 - Dec 10 2024 Washington DC (USA) [https://arpa-e.energy.gov/news-and-events/events/spin-polarized-fusion-spf-workshop]

[32] J. F. Parisi, A. Diallo, J. A. Schwartz, *Simultaneous enhancement of tritium burn efficiency and fusion power with low-tritium spin-polarized fuel*, Nucl. Fus. **64** (2024) 126019.

[33] J. F. Parisi *et al.*, *Doubling fusion power with volumetric optimization in magnetic confinement fusion devices*, Phys. Rev. Res. **7** (2025) 013139.

[34] J. W. Bae *et al.*, *Neutronics analysis of spin-polarized fuel in spherical tokamaks*, Nucl. Fus. **65** (2025) 086051.

[35] G. Giunchi, *The Reactive Liquid Infiltration (RLI) Technique for the Bulk Reaction to* MgB_2, in Ed. R. Flükiger "MgB_2 *Superconducting Wires – Basics and Applications*, (World Scientific, 2016, Singapore).