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BANDO FIRB - PROGRAMMA "FUTURO IN RICERCA"

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Linea d'intervento 2

1 - Research program title

Polarized fusion control by initial-state polarization: experimental investigation of the spin effects in nuclear fusion reactions (d+d, d+3He) at low energy.

2 - Research program duration

48 months

3 - Principal Investigator

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4 - Abstract of the Research Program

The dependence of our society on non-renewable energy sources sets urgent and complex warnings concerning the compatibility of the progress of our economy with the preservation of the environment and of the natural resources. Furthermore, it also concerns the difficult equilibrium between raw materials importing and exporting countries and between rich and emerging economies. Based on this context of increasing uncertainty on the long term progress of our society, nuclear energy sources are being recently revaluated, especially those that ensure a high security level and a limited impact on the environment.

Nuclear fusion is an ideally safe and clean energy source: the reactions prevent the production of unwanted long term radioactive nuclear waste, are not self-powering and cannot proceed without external operations. Differently from nuclear fission based reactors, those based on nuclear fusion are subject to a much lower probability of catastrophic events resulting in dispersion of radioactive materials in the external environment and in a threat for human being. As a matter of fact, the products of fission reactors continue to generate heat through beta decays for many hours or days after the reactor power off, thus running the risk of meltdown of the reactor. On the contrary, nuclear fusion requires controlled conditions of temperature, pressure and magnetic fields in order to generate energy. In case of accident, these parameters would suddenly change and energy production would cease immediately. In fusion based reactors, the process is so delicate to be intrinsically safe, thus requiring much simpler control systems. Although the volume of plasma in a fusion reactor can reach a volume as large as 1000 m^3 or more, the density is relatively low and the total quantity of fuel is very small (typically a few grams). Without the additon of new fuel the reaction ceases within a few seconds. On the contrary, a fission reactor contains in general enough fuel to run for years and it is not necessary to add new fuel in order to maintain the reaction.

Unfortunately, the technological difficulties related to nuclear fusion reactions are not solved yet. The construction of the first economically convenient fusion reactor needs decades. However thanks to the ITER project (low intensity magnetic confinement) and the continuous research in the field of inertial confinement (high density) nuclear fusion, the perspectives for nuclear energy could enter a new era.

In this framework, new dedicated methodologies able to solve or overcome the actual technological limits could accelerate the long process of technical optimization of fusion reactors. The idea of polarized fusion was introduced in the '80s: it would offer several advantages with respect the unpolarized fusion, i.e. rate enhancement and neutron flux reduction.

In order to quantify the possible benefits of polarization in nuclear fusion reactions, high precision experimental data on spin correlations of the cross sections of the low energy reactions 3H(d,n)4He or 3He(d,p)4He and of Deuterium fusion D(d,p)3H and D(d,n)3He are needed.

The interest on these measurements is interdisciplinary. In fact, these reactions are of great importance for nuclear astrophysics and cosmology, as they represent the basic processes of primordial nucleosynthesis and stellar evolution. In addition, polarization observables are useful to test theoretical model calculations on many-body nuclear reactions.

The experimental configuration requires polarized beams and/or gas targets. The experiment also requires the use of polarimeters for the measure of the polarization in the initial channel. The required experimental devices are very similar to those already developed in the framework of the PAX collaboration and currently in operation at Juelich for tests of polarization of beams through spin-filtering. It is worth to stress that the Ferrara SpinLab is the only place in Italy where it is possible to develop a polarized atomic beam source to be employed is these kind of studies.

The project foresees the realization of a facility for the study of polarized nuclear fusion of light elements at low energy (10-100 keV) and a first set of measurements.

5 - Keywords

1. *Polarized nuclear fusion*
2. *Fusion energy*
3. *Multi-body nuclear forces*
4. *Big-Bang nucleosynthesis*
5. *Stellar evolution*

6 - ERC (European Research Council) research fields

PE Mathematics, physical sciences, information and communication, engineering, universe and earth sciences

PE2 Fundamental constituents of matter: high energy, particle, nuclear, plasma, atomic, molecular, gas, and optical physics
PE2_4 Nuclear physics

PE7 Universe science: astro-physics/chemistry/biology/geology; solar system; stellar, galactic and extragalactic astronomy, cosmology; space science, instrumentation
PE7_14 Cosmology

PE2 Fundamental constituents of matter: high energy, particle, nuclear, plasma, atomic, molecular, gas, and optical physics
PE2_5 Gas and plasma physics

7 - Scientific curriculum of the Principal Investigator

Marco Contalbrigo was born in 07/12/1971. He graduated in Physics in 1996 at University of Padova with the thesis: "Search for tau neutrinos in the neutrino beam of SPS at CERN".

In 1997 was awarded with the prize "Prof. Italo Filosofo" by the Istituto Veneto di Science, Lettere ed Arti for the best thesis in Physics at University of Padova and received an INFN fellowship for postgraduate students in sub-nuclear experimental physics. In 2001 he got the PhD in Physics at University of Ferrara with the thesis: "Precise measurement of the KL -> pi0gg decay". He got post-docs positions from 2001 to 2005 at University of Perugia and University of Ferrara. Since 2005 he is INFN researcher at the Ferrara Section of INFN.

He is author of 80 publications on International journals with referee and has published several works on proceedings of International conferences.

Brief summary of his scientific activity:

Marco Contalbrigo is involved in the experimental and phenomenological study of the fundamental interactions of elementary particles.

He began his scientific activity in the field of electro-weak physics with cosmological implications at the NOMAD experiment (CERN, Geneva), searching evidences of neutrino oscillations in the range of large masses, and at NA48 (CERN, Geneva), for the study of CP violation in the neutral kaon sector.

After the PhD he began to work in the field of spin physics and nucleon structure. He is a member of the HERMES collaboration (DESY, Hamburg) and has actively contributed to the study of spin dependent partonic functions of the nucleon. In particular he has coordinated the inclusive analyses and is currently coordinator of the analyses on the transverse spin effects.

He is among the proponents of the PAX experiment for the physics of polarized antiprotons. He is deputy-responsible for the silicon tracking detector for the experiments on the polarization of antiproton beams.

He is promoter of precision measurements of spin effects in deep-inelastic scattering at Jefferson Lab (Newport News, VA, USA) and is spokesperson of one of the experiments recently approved.

He contributes to the technological development of nuclear polarized gas targets in collaboration with the SpinLab laboratory at University of Ferrara.

He has presented his results in a number of International conferences. The most recent contributions are listed below:
**) "Detectors at storage rings" at STORI05, May 2005, Juelich-Bonn;*
**) "The PAX Polarized Antiproton eXperiment" at Transversity 2005, September 2005, Como;*
**) "Investigation of the Nucleon Spin Structure at HERMES with longitudinally polarized targets" ans "Antiproton--Proton Scattering Experiments with Polarization" at Spin-05, October 2005, Dubna, Russia;*
**) "The PAX Polarized Antiproton eXperiment" at the XLIV International Winter Meeting on Nuclear Physics, Janaury 2006, Bormio;*
**) "PAX project at FAIR" at the Caucasian-German School and Workshop on Hadron Physics, September 2006, Tbilisi, Georgia;*
**) "Measurement of Transverse Asymmetries from Interference Fragmentation at HERMES" at SPIN 2006, October 2006, Kyoto, Giappone;*
**) "Spin Physics at HERMES" at QCD@work 2007, June 2007, Martina Franca;*
**) "The status of the PAX project at FAIR" at the The 6th Cirum-Pan-Pacific Symposium on High Energy Spin Physics, July 2007, Vancouver, Canada;*
**) "Transverse Spin Physics at HERMES" at SPIN 2008, October 2008, Charlottesville - VA, USA.*
He is among the organizers and editors of the following conferences held in Ferrara: QCD-N02, April 2002 and Transversity 2008, May 2008.

8 - Scientific pubblications of the Principal Investigator

nº	Publication
1.	*M. Stancari, L. Barion, M. Capiluppi, G. Ciullo, CONTALBRIGO M., P.F. Dalpiaz, A. Drago, P. Lenisa, M. Statera, E. Steffens, M. Wang (2008). Low conductance injection tubes for storage cell targets. NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH. SECTION A, ACCELERATORS, SPECTROMETERS, DETECTORS AND ASSOCIATED EQUIPMENT, vol. 594; p. 126-131, ISSN: 0168-9002, doi: 10.1016/j.nima.2008.06019*
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5.	*M. Stancari, G. Ciullo, S. Atutov, L. Barion, M. Capiluppi, CONTALBRIGO M., P.F. Dalpiaz, F. Giordano, P. Lenisa, M. Statera, M. Wang (2005). Estimates of intra-beam scattering in atomic beam sources. In: 16th international spin physics symposium (SPIN2004). Trieste, 10/10/2004-16/10/2004, Toh Tuk Link: World Scientific Publishing, p. 779-782*
6.	*M. Statera, M. Stancari, V. Carasitti, G. Ciullo, F. Evangelisti, CONTALBRIGO M., P.F. Dalpiaz, P. Lenisa (2006). A Test Bench for Small Multipolar Magnets for a High-Intensity Superconducting Atomic Beam Source. IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, vol. 16; p. 297-300, ISSN: 1051-8223*
7.	*M. Statera, M. Capiluppi, G. Ciullo, CONTALBRIGO M., P.F. Dalpiaz, P. Lenisa, M. Stancari (2007). The Field Mapping at Low Temperature of a NbTi Setupole. In: CRYOPRAGUE 2006 PROCCEDINGS OF ICMC '06, TWENTY FIRST INTERNATIONAL CRYOGENIC ENGINEERING CONFERENCE AND 9TH CRYOGENICS. PRAGA, 17/07/2006 - 21/07/2006, Praga: ICARIS Ltd, vol. 2, p. 199-202*
8.	*CONTALBRIGO M. (2005). Detectors for storage rings. In: Nuclear physics at storage rings. Juelich, 23-26 May 2005, BONN, p. 373-380*
9.	*RATHMANN F, LENISA P, STEFFENS E, CONTALBRIGO M., P. FERRETTI DALPIAZ, KACHARAVA A, LEHRACH A, LORENTZ B, MAIER R, PRASUHN D, STROHER H (2005). A method to polarize stored antiprotons to a high degree. PHYSICAL REVIEW LETTERS, vol. 94; p. 014801-1-014801-4, ISSN: 0031-9007*
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9 - List of the Research Units (UR)

Unit	Associated Investigator of the Research Unit Program	Degree	Institute denomination	Department/Institute	Months/ man
1	*CONTALBRIGO Marco*	*Ricercatore*	*Istituto Nazionale di Fisica Nucleare*		*98*
2	*PAPPALARDO Luciano Libero*	*Dottore di Ricerca*	*Università degli Studi di FERRARA*		*80*

10 - Research units description

The establishment of an experimental facility for the measurement of cross sections of polarized fusion reactions between light nuclei is a complex task which necessarily needs the involvement of various research groups. The project foresees the collaboration between four European Institutions (two of which are Italians) with a precise division of duties and responsibilities.

The Italian members of the two Research Units involved are active since many years in the field of the physics of the nucleon spin within the context of various International collaborations. Since 1997 they are members of the HERMES Collaboration: the experiment, located at the HERA storage ring at DESY (Hamburg) studies the spin structure of the nucleon in Deeply Inelastic Scattering (DIS) of polarized electrons off polarized nucleons. The members of the two Research Units have significantly contributed to the results of the experiment. Among its members is the responsible for the polarized target since 2000, and Marco Contalbrigo, who has been responsible for the analyses of inclusive events with longitudinally polarized targets and is currently responsible for the analyses of semi-inclusive events with transversely polarized targets.

The Italian members of the Research Units are among the authors of proposals of DIS experiments at Jefferson Lab aimed to the study of transverse spin and momentum effects of the nucleon in a kinematical regime complementary to the HERMES (and the other running experiment COMPASS) one and with a luminosity higher by many order of magnitudes. In particular, Marco Contalbrigo is spokesperson for an approved experiment on the spin-orbit effects of the nucleon with a 12 GeV beam.

The Italian members of the Research Units have presented, together with foreign collaborators, the PAX project, "Polarized Antiproton Experiment". Among the memebers of the Research Units is the current PAX co-spokesperson. PAX is embedded within the new "Facility for Antiproton and Ion Research" (FAIR) for an important European hadron physics laboratory at GSI (Darmstadt). The proposal is based on the possibility to obtain, for the first time, a high-quality beam of polarized antiprotons, to be employed in the study of transverse spin effects of the nucleon in Drell-Yan (DY) processes and p-pbar elastic scattering. The use of a polarized target, similar to the HERMES one, internal to the beam pipe or the creation of a polarized p-pbar collider will allow to measure for the first time doubly-polarized Drell-Yan reactions which, in turn, allow to access important unmeasured observables related to the nucleon structure. The Research Units are currently involved in experiments aimed to create polarized antiprotons through the spin-filtering method. This process makes advantage of the dependence of the elastic scattering cross section on the spin of the colliding particles and is based on the selective extraction of a certain spin state through the interaction of the circulating beam with a fixed polarized gas target internal to the beam pipe.

The Research Unit coordinated by Marco Contalbrigo is composed by members of the staff of the Ferrara section of the Istituto Nazionale di Fisica Nucleare (INFN) and by foreign personnel from the European Institutions involved in the project:

**) "Institute fur KernPhysick ForschungsZentrum Juelich" (IKP FZ Juelich), Germania*

**) "Petersburg Nuclear Physics Institute, Russian Academy of Sciences", (PNPI RAS), Gatchina, Russia.*

The Ferrara section of INFN, in collaboration with the IKP of Juelich, is involved in the construction of a silicon detector for experiments with polarized antiprotons beams propaediutic for the PAX project. The detector is conceived to measure the few MeV recoiling protons and deuterons, to operate in vacuum (in order to allow the detection of low energy particles), to allow the tracking of particles with different energies and the identification of different isotopes (using variuos silicon layers with different thickness) and to self-generating the trigger for the acquisition. The detector is based on large area (5x5 or 10x10 cm^2) wafers of silicon strips in order to ensure a wide solid angle coverage and a high luminosity. The strips are double-faced to allow the spatial reconstruction of the hits. The features of this detector are particularly suitable for the detection of reaction products of nuclear fusion of light nuclei. An important part of the R&D for the detector can thus be exploited for the present project.

The full technical support is ensured by the involvement of the responsible of the Mechanical and of the Electronic Service of the INFN Ferrara. It is worth to mention that the Mechanical Service has produced the storage cells of the HERMES target and has been responsible for the installation of the cells on the HERA storage ring at DESY. On the other hand, the Electronic Service is developing part of the readout electronics (the trigger and the prescaler boards and the software for the control of the front-end chips and the ADCs) for the PAX detector. The Research Unit is going to set up a new laboratory in Ferrara, dedicated to the calibration and characterization of the silicon detectors.

The Research Unit will contribute, in collaboration with the IKP Institute of Juelich, to the assembly of the silicon detector and the related read-out electronics as a bonus of the development of the silicon tracker for (anti)protons and deuterons for future experiments with polarized beams.

In addition, the Unit ensures the link and the collaboration with the foreign research groups involved in the project.

The Petersburg Nuclear Physics Institute of the Russian Academy of Sciences, Gatchina, Russia (PNPI RAS), has the responsibility for the ion source for the beam and the 100 keV accelerator facility, and offers its experimental halls for the installation of the experimental apparatus. The PNPI personnel collaborating to this project has the required skill, since was responsible of the cooling system design of the silicon detector for the tracking of the Lambda decays at HERMES experiment (DESY), of the ABS dissociator cooling system at COSY, of the realization of a 10k lt/sec cryogenic pump for the scattering chamber of PAX experiment. They also pursuit a research program for the molecular polarization of hydrogen and deuterium based on recombination of polarized atoms.

The Institut fur KernPhysick of the laboratory ForshungsZentrum Juelich, Germany (IKP FZJ), provides a lambshift polarimeter for the measurement of the polarization of the gas target. The IKP personnel has already designed and realized such kind of polarimeter and is responsible for the cryogenic system of the superconducting solenoid of the WASA experiment at COSY.

The Research Unit coordinated by Luciano Pappalardo is composed by staff of the University of Ferrara. The Unit has acquired a great experience in the field of polarized gas targets. It handled the polarized gas target of the HERMES experiment since 2000. The responsibility covered the injection system for the polarized and *non-polarized gas, the diagnostic devices of the target and the control device of the cryogenic system. The latter was extended from 2006 to the solenoid superconducting magnet of the recoil detector. The Research Unit also leads the Spinlab laboratory of the Ferrara Physics Department, dedicated to the R&D on high intensity Atomic Beam Sources (ABS). Spinlab hosts two ABSs: one (ABS1) is dedicated to test the optimization of the atomic dissociation of a molecular gas, and the other (ABS2) is provided with the polarization systems. In addition, a cryogenic test facility for superconducting magnets is run. This facility is used for the magnetic field mapping of superconducting magnets to be employed in ABSs and in storage rings. The skills of the Unit will be exploited in the planning and the construction of the magnetic system dedicated to the conservation of the polarization of the beams. The Unit has the responsibility for the completion and the installation of an atomic beam source for the target beam by upgrading the ABS2 currently running at the Spinlab facility.*

11 - Research program scientific aims and expected results

Nuclear fusion reactions relevant for energy production are limited to light nuclei, essentially the isotopes of Hydrogen and Helium. The reaction rates strongly depends on the height of the Coulomb barrier and only highly exothermic reactions (high positive Q value) can be exploited. Therefore the most used reactions deal with four or five nucleons (Deuterium-Triton, Deuterium-Helium and Deuterium-Deuterium fusions) in the 10-100 keV energy range.

The most interesting reactions concerning the energy production from fusion are:

D-T fusion: [3H(d,n)4He] d + 3H -> n + 4He + 17.6 MeV

D-He fusion: [3He(d,p)4He] d + 3He -> p + 4He + 18.3 MeV

The D-T fusion reaction is the most convenient due to the larger cross section and the higher energy density at lower temperatures of the plasma. The Deuteron is a natural isotope of Hydrogen and is easily achievable. The Triton is also an isotope of Hydrogen but, being radioactive (12.32 years half-life), it is only available in very limited quantities. As a consequence, most of the reactors make use of Lithium isotopes for the production of Triton through the reaction: n + 6Li -> T + 4He and n + 7Li -> T + 4He + n, where the interacting neutron is produced by the simultaneous D-T fusion reactions. The fusion of 6Li is slightly exothermic and contributes to the energetic gain of the reactor. The combustion of 7Li is endothermic and does not prevent the absorption of the neutron. The availability of Lithium is smaller than that of Deuterium, but still sufficient to fulfil the human demand of energy for thousand of years.

However the D-T fusion has some disadvantages: it produces a lot of neutrons that cause the activation of the reactor structure, only nearly 20% of the fusion energy is released to the charged particles (the rest of the energy goes to the neutrons) thus significantly limiting the efficiency of exploitation of the produced energy; requires the use of Lithium which highly flammable and of Triton which, similarly to Hydrogen, is hard to contain and could escape the reactor.

Particularly serious is the problem related to the production of neutrons. The 14.1 MeV neutron produced in the reaction should be absorbed with proper screenings and can cause the activation and modification of the screening materials. These problems reflect immediately into serious economical issues. The neutron flux predicted for a commercial D-T fusion reactor is roughly 100 times higher than for a standard fission reactor. The experimentation of new materials is under progress but a real application on a fusion reactor will be only possible for the reactor generation next to ITER. For instance, after a single test at the JET reactor, the biggest one ever fuelled with this combustible so far, the vacuum chamber was so activated that operations in loco were unfeasible for up to one year after the end of the test.

The Deuterium-Helium fusion reaction, although less energetically convenient, has the important advantage that does not produce neutrons. It could then represent an ideal alternative to the D-T reaction, which is affected by the problems discussed above. On the other hand, the D-H reaction requires a higher temperature for the ignition. Furthermore, a reactor based on this reaction would not be completely neutron free due to the simultanous (although with smaller cross section and lower energy of the products) D-D fusion reactions:

D-D fusion: 2H(2H,n)3He + 3.3 MeV and 2H(2H,p)3H + 4.0 MeV.

The idea of polarized nuclear fusion was already introduced in the '80s. It offers a number of advantages with respect to the traditional (unpolarized) fusion:
**) control of the neutron flux through the suppression of reactions with neutrons in the final state in favour of reaction with charged particles as products;*
**) control on the direction of the emitted reaction products*
**) enhancement of the reaction rates*
Some of the benefits above would allow a lower ignition limit and economically advantageous conditions of the use of the reactor, thanks to the lower degree of radiation damage and activation of the structures. In particular, the conversion in heat of the neutron energy would require much simpler and durable devices.

Some of the basic aspects of the polarized nuclear fusion need to be clarified before quantifing the effective potentiality of this energy source. To evaluate the polarization effects on the fusion energy high precision experimental data on low energy fusion reactions are needed. The existent experimental data on these reactions deal, in most of the cases, with interactions between unpolarized nuclei. In reality, the cross section can have an important dependence on polarization with crucial implications for the design parameters of the next generation reactors. So far, no spin correlations of the cross section have been measured: the predictions currently available on polarized fusion are based on a world data of much simpler observables. Theoretical calculations of these multi-body cross sections are complicated and the accuracy of the current predictions is not known. A final answer can only be provided by direct experimental measurements.

At the low beam energies under consideration (Deuterium beam of 107 keV for the 3H(d,p)4He reaction and of 430 keV for the 3He(d,p)4He reaction, respectively), both reactions proceed through S-wave resonant states. Experimental evidences have shown that these resonant states are nearly due to pure J^pi=3/2^+ states with a tiny contamination (of the order of 1%) of J^pi=1/2^+ states and of higher partial waves. Since transitions occur basically only through a single matrix element, theoretical predictions of the cross section and of polarization related observables are reliable. According to these predictions, nuclear fusion reactions with polarized initial state particles would result in an enhancement (up to 50%) of the yield and in a lowering of the break-even point of the reactor.

Differently from the five-nucleon cases, the mechanism of the two four-nucleon reactions above is very complicated due to the contribution of 16 complex matrix elements that include S, P and D-wave interactions already at low energy.

An interesting point is that the products of fusion reactions with polarized particles in the initial channel are emitted anisotropically. This fact can, in principle, be exploited by addressing the produced neutrons in specific directions. As a result the neutrons can be more easily confined and their harmful effects minimized. It was argued that neutron production in D-D fusion reactions can be substantially reduced by using polarized beam and target deuterons. This, indeed, would result in the involvement of a quintet state (spin=2), which in turn would require spin-flip transitions that are forbidden by the Pauli principle (by neglecting the D-wave contribution in the deuteron). The available indirect experimental evidences are not conclusive: a direct measurement is still missing and would then be highly desirable.

The reactions above are gaining an increasing interest for several reasons.

The study of polarized nuclear reactions is an important field to
theoretical calculations on multi-body systems. The progresses for the four-nucleon case are relatively slower with respect to the three-nucleon case due to the much more complicated structire and to the problems related to the penetrability of the Coulomb barrier at low energy. The comparison between experimental results and theoretical predictions show that the discrepancies, already unsolved for the three-nucleon case, are even more severe for the four-nucleon case. The effects of polarization at low energy are larger for the four-nucleon system due to the involvement of P-wave and D-wave contributions in the initial channel.

Furthermore experimental data on low energy Deuterium fusion reactions are of great and actual interest also for astrophysics. The cross sections of fusion reactions of light elements, indeed, dominate the theoretical uncertainties on the primordial nucleosynthesis and have a crucial role in stellar evolution. Thanks to recent measurements of cross sections, observation of the abundance of elements and of the anisotropy of the electromagnetic cosmic background, it will be possible to define more tight constraints on nuclear astrophysics, and in particular for stellar and cosmological models.

The present project proposes a detailed experimental study of light elements polarized fusion reactions at low energy. The expected results have important implications in several fields: energetic issues related to fusion reactors, theories for many-body nuclear systems and predictions for stellar evolutions and formation *of the Universe.*

In particular the project foresees the realization of a facility for the measure of nuclear fusion reaction cross sections and the fulfilment of a first run of measures.

The experimental set-up is based on the following main apparatus:

**) polarized atomic beam: polarized atomic beam sources (ABS) are being developed at the SpinLab laboratory in Ferrara and are in use in several International laboratories. They are based on the dissociation of a molecular gas, the subsequent selection of hyperfine states with nuclear polarization (operated with a Stern-Gerlach method) and radio-frequency transitions between hyperfine states.*

**) polarized ion beam: atoms from a second polarized atomic source are ionized and accelerated, by an electrostatic field, up to the interaction point. The ion beam acceleration fix the fusion reaction energy. The polarization of the ion beam can be measured through the interaction with unpolarized targets in nuclear reaction with known analyzing power (single-spin asymmetries).*

**) Lambshift polarimeter: the polarization of the atomic beam has to be constantly monitored. The lambshift polarimeter allows to measure the nuclear polarization of a Deuterium atomic beam within a few seconds with a precision of 1%, by measuring the intensity of Lyman-alpha transitions between metastable states selected in a spin filter.*

**) silicon detector: for the detection of reaction products with energy of a few MeV it is mandatory to locate the detectors in vacuum. The silicon detectors allow to completely characterize the event as they can measure the position and energy of the detected particles and can discriminate between the various isotopes through the relation between kinetic and released energy. The read-out system allows to extract the acquisition trigger directly form the silicon detector.*

The expected results are listed below:

**) by the end of the first year: upgrade and optimization of the Atomic Beam Source currently running at Spinlab; simulations for the optimization of the interaction point and the geometry of the detector; design of the electrostatic accelerator; preparation and shipping to Gatchina of the ion source and the lambshift polarimeter from IKP FZ Juelich;*

**) by the end of the second year: characterization of the ion beam source and electrostatic acceleration construction; purchasing of the silicon detectors; test and calibration of the detectors; assembly of the frame and of the cooling system of the detector; completion of the power supply and of the read-out electronics of the detector; shipping of the Atomic Beam Source from Ferrara to Gatchina; arrangement and characterization of the target jet and the polarimeter; start up of incident beam (ion source and electrostatic accelerator);*

**) by the end of the third year: shipping of the detector to Gatchina and set up of the full interaction point; commissioning of the facility for the study of the nuclear reactions with the Atomic Beam Source (target jet), ion source (incident beam) with electrostatic accelerator, polarimeter and detector for the reaction products; characterization of the incident beam with the measurements of a know analysing power, for instance using the reaction 3He(polarized-D, p)4He. The operation of the various apparatus will be documented by presentation to international conferences or publications on specialized international journals (e.g. Nuclear Instruments and Methods). The initial configuration will be dedicated to the study of the D-D fusion reaction with polarized Deuterium beams. Further extensions will eventually make use of polarized target jets of Helium and Triton for the study of the complete set of fusion reactions described above;*

**) by the end of the fourth year: completion of a first run of measurements and publication of the relative results in conference proceeding or articles in international journals. The first run of measurements will be dedicated to the D-D fusion in the energy interval with the largest cross section. These measurements correspond to the most favourable experimental conditions and are among the most interesting ones, due to the complex phenomenology associated to the polarization of the interacting (beam and target) nuclei.*

The project also foresees:

**) the fulfilment (in case of continuation and extension of the present project) of a comprehensive program of measurements at the realized facility and the development of a 3He target jet;*

**) the feasibility study for the use of a polarized target: with respect to a bare atomic beam from an ABS, the use of a storage cell for the polarized atomic gas, to be located along the axis of the ion beam, would allow to increase to up to two order of magnitudes the effective density of the target. However, the cell walls should be very thin in order to allow the detection of the reaction products (teflon cell down to 5 micron are now being produced). The walls of the cell are also required to minimize the depolarization effects on the stored gas in collisions with the cell surface. The cell has to be operated within a magnetic field needed to maintain the polarization of the gas and the surface of the silicon detector should increase to cope with the enlarged interaction region.*

**) the collaboration with other groups on the delicate issue of the injection of polarized fuel into a fusion reactor. In particular the Research Unit recently began to collaborate with Jefferson Lab for measures of deep inelastic scattering with the CLAS experiment at Jefferson Lab, USA. The experiment foresees the use of solid targets with polarization frozen by the joint action of low temperature and strong magnetic fields. A possible application of this technology can in principle be the production of polarized bullets to be injected into the core of fusion reactors. The injection of fuel in the form of solid bullets is one of the most studied methods for fusion since it would allow to feed the reaction directly from the centre of the plasma. In this sense this technique would be much more efficient than the traditional gas flux, which interacts mostly with the periphery of the plasma.*

The project, if approved, will allow the realization of a laboratory for the study of a comprehensive program of measurement of fusion reactions which are of fundamental importance not only for Physics and Astrophysics but also for the future plan on energy demand.

12 - National or international scientific background

The most promising nuclear fusion reactions are:

D-T fusion: 3H(d,n)4He

D-H fusion: 3He(d,p)4He

D-D fusion: D(d,p)3H and D(d,n)3He.

Other possible reactions with heavier nuclei (i.e. p + 6Li, p + 11B, 3He + 3He, p + 9Be) have energy density smaller by order of magnitudes at the relevant temperatures.

The idea of polarized fusion reactions dates back to the 80s [1-4]. The polarization of the initial state particle would allow an enhancement of the reaction rate and a stronger control on the neutron flux with the possibility of relevant economic benefits.

The energetic range of interest for the reactions listed above is between 10 and 100 keV. At these energies, the rates of the twin reactions 3He(d,p)4He and 3H(d,n)4He are dominated by the nearly pure S-wave J=3/2^+ resonance. Using unpolarized fuel this resonant channel should compete with the very low populated J=1/2^+ in agreement to the statistical weight ratio of 4/2. The cross section for unpolarized particles is given by the incoherent sum of the various transitions (matrix elements). By preparing the transition in the pure configuration J=3/2, M=3/2 the reaction rate would ideally enhance by 50%.

The current theoretical predictions are based on a number of fusion reaction measurements. However the measured observables are usually referring to the unpolarized case or to single spin asymmetries (analysing powers). Refer to [5-13] for the D-T fusion, to [13-19] for the D-H fusion, to [12-14, 20-25] for the D(d,n)3He fusion and to [12-14, 20-23, 26, 27] for the D(d,p)3H fusion. Some measurements also consider double spin asymmetries (spin correlations) [28,29] but *are rare and limited to small ranges in energy and angles. The experimental measurements [16,28,29], suggesting that channels different from the J=3/2 (S-wave with J=1/2 and higher partial waves) only provide for small contributions, endorses predictions of an enhancement of the cross section for polarized initial states. Refer to [30,31] for detailed discussions on the spin dependence of these reactions, their connections with the polarization observables and the relative partial waves amplitudes.*

A factor of 1.5 in the rate of the Deuterium-Helium fusion reaction was assumed in the planning of the ARTEMIS thermonuclear reactor [32].

The theoretical calculations of the cross sections involved are complicated due to the many-body nature of the reactions. The accuracy of these calculations is not well known due to the use of certain approximations concerning the many-body interactions. Only direct experimental measurements of these cross sections can provide final answer with acceptable precision. It is even not clear if the electron-screening enhancement of the cross section at low energies [33] might have any influence for the polarized fusion.

The reaction mechanism for the four-nucleon case is more complicated than the five-nucleon case, since 16 complex matrix elements including S, P and D-waves contribute at low energy. The interest for these reactions is increasing for many reasons. It is an important field to test theoretical calculations. Some methods are based on Faddev-Yakubowski [34] like calculations or Refined Resonanting Group Method, RRGM [35] like calculations. Others more recent are based on effective theories like the Chiral Perturbation Theory. The progresses for the four-nucleon case are relatively slower due to the much more complicated structure with respect to the three-nucleon case and due to the problems related to the solution of the penetrability of the Coulomb barrier at low energy. The discrepancies between experimental results and theoretical predictions, already unsolved for the three-nucleon case, are even more severe for the four-nucleon case [36]. The effects of polarization at low energy are larger for the four-nucleon system due to the involvement of P-wave and D-wave contributions in the initial channel.

It was argued that neutron production in D-D fusion reactions can be substantially reduced by using polarized beam and target deuterons. This, indeed, would result in the involvement of a quintet state (spin=2), which in turn would require spin-flip transitions which are forbidden by the Pauli principle. So far measurements with polarized beam and target Deuterium have never been performed. The current indirect experimental evidences are not conclusive [37,38]. Therefore, a direct measure would be highly desirable.

The major uncertainties on primordial nucleosynthesis arise from the cross sections of the nuclear reactions D(d,n)3He, D(d,p)3H, D(p,gamma)3He, 3He(alpha,gamma)7Be and 3He(d,p)4He [39,40] some of which are part of the present project.

The realization of polarized nuclear fusion can in principle face new difficulties and requires innovative and specific solutions. For instance, difficulties might arise in the preparation of polarized fuel, in the achievement of an intense polarized atomic Triton, Deuteron or Helium beam or of bullets filled with liquid or solid polarized fuel; the injection of the polarized fuel into the core, and the depolarization during the injection and the ignition. For some of these issues predictions are available [1] while others are being tested [41,42].

The great interest on the subject of polarized nuclear fusion is demonstrated by the ongoing activity in Japan [32,43] and in America [41,42]. It would then be highly derirable that similar efforts and skills in such an innovative and strategic field for the future society could be undertaken also in Europe.

In order to verify the effects of polarization in fusion reactions of light nuclei it is necessary to measure spin correlations. The formalism for a reaction between spin-1 (and/or spin-1/2) particles is relatively complicated. However it becomes simpler if one considers the same polarization axis for both beam and target (relevant case for the fusion) and if the states can be prepared with a pure vector or tensor polarization. These requirements need specialized skills which are well established within the two Research Units involved in the project.

The Italian members of the two Research Units involved in the project are active since many years on the study of the polarized Hydrogen and Deuterium targets [44-48]. These targets allow to reach degrees of polarization as high as 80%, have the important advantage of a zero dilution from unpolarized materials (differently from the solid targets), and can reverse the polarization sign within a few milliseconds. It is worth to emphasize that the SPINLAB of the University of Ferrara is the only place in Italy where it is possible to develop a polarized atomic beam source equipped with dedicated diagnostic systems. Polarized gas target have been successfully used internally to the HERA storage ring a DESY (Hamburg) for the HERMES experiment, under the responsibility of the Italian members of the Units [49-51]. The same targets are now being used within the program of (anti)proton beam polarization propaedeutic for the PAX experiments [52-54]. The skills of the Research Units also include the construction of storage cells for polarized gas [55,56], the planning and testing of superconducting magnets at the operation temperatures [57,58], and the management of vacuum and cryogenic systems in the experimental areas (HERA, COSY, Spinlab).

The foreign members from the IKP FZ Juelich and the PNPI San Petersburg collaborate with the Ferrara group on the PAX project [52,54]. They are actively involved in the running of the polarized target internal to the COSY ring [59-62], are skilled in beam polarimetry [63] and have developed a Lambshift polarimeter for the measure of the polarization of the atomic targets [64,66].

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13 - Description of the research

It is not clear yet if realistic calculations (Faddeev-Yakubowski or Chiral Perturbation Theory + Coulumb) will be available at the energies relevant for the fusion energy and the astrophysics sector. Thus it is fundamental to get direct measurement of spin correlations in fusion reaction of light nuclei, i.e. to quantify the quintet suppression in the deuterium-deuterium fusion. This project aims the realization of an experimental facility for such kind of measurements.

Although predicted long time ago, these measurements have never been studied in the past due to serious difficulties. Among them is the relatively low cross section. The use of solid polarized Deuterium is particularly complex [1-3]. It has the additional disadvantage of a non-zero contamination due to the presence of other (unpolarized) elements in the target. Moreover the low energetic products would hardly excape the solid target and be revealed.

The proposed solution is represented by the use of high density polarized atomic beams colliding in a certain region delimited by suitable detectors for the reaction products.

The target (gas) jet can be generated by a source of polarized atomic beams (ABS). The source consists of a dissociator (that dissociates the molecular gas injected into the system), a beam line equipped with a Stern-Gerlach device that allows to select the desired spin states and a radio-frequency cavity that allows transitions among the hyperfine states. This kind of sources is being used since many years and has demonstrated high stability and reliability as well as the possibility of reaching high degrees of polarization (on the level of 80%) with systematic effects well under control (of the order of 3%). Examples are the source used as polarimeter for the high energy (100-500 GeV) proton beam at RHIC, BNL, USA [4] and the source used in the HERMES target, internal to the HERA storage ring at DESY (Hamburg) [5], under the responsibility of the Italian members of the Research Unit involved in the present project since 2000. The HERMES ABS has been upgraded and it is currently running at COSY, Juelich, to be used in experiments dedicated to the polarization of protons (antiprotons) beam according to the program of the PAX collaboration [6].

The incident beam can be obtained by ionizing the atomic beam of a second ABS. The following electrostatic acceleration defines the reaction energy. An alternative is to use a single ABS, ionizing the target (gas) jet after the passage through the interaction region, accelerating and bending it in such a way to intersect perpendicularly the target jet in the interaction region. The scheme based on two sources offers a greater flexibility in dealing with the beam optics and in the manipulation of the spin, and might provide a higher luminosity. The expected yields are relatively low (of the order of 1 hit every 100 seconds) therefore a high stability of the apparatus and automated measures able to trigger and select the events of interest from the background are required.

The quantities to be measured are the angular distributions of selected terms of the spin correlation of the differential cross section based on different combination of the three possible spin states of both the beam and the target nuclei. The single spin terms (of the beam or the target), known as analysing powers, are also part of the cross section and need to be measured or extracted from previous data. It is crucial, for the flexibility and the simplicity of the measure, that the sources allow to make beams with vector and tensor polarization and that it is possible to orientate the polarization along any direction, for instance through electrostatic bending of the beam or magnetic fields (spin precession).

For the detection of the reaction products, the natural choice for the detector is represented by solid state detectors surrounding the intersection region in such a way to cover a big portion of the phase space available for the reaction. The silicon detectors can be operated in vacuum in order to reveal low energy particles. In addition, they allow to track the reaction products, to measure their kinetic energy (if stopped within the detector) and to identify the isotopes with Delta_E ? E technique. If equipped with a dedicated electronics they can generate the trigger without the need of external detectors (e.g. scintillators). Examples are the silicon telescopes being developed at Juelich which consist of three silicon layers with different thickness (70, 300 and 5000 micron) [7] and silicon detectors used in Nuclear Physics [8,9].

The polarization of both the beam and the target (gas) jet needs to be regularly measured and monitored. Possible measuring devices for the target polarizations are the Lambshift polarimeter in operation at Juelich [11] or the Breit-Rabi polarimeter operated by the Ferrara group for the PAX experiment [10,11]. For the incident beam one can use the analyzing power previously measured in low energy reactions such as 2H(d,p)3H, 2H(d,n)4He or 3He(d,p)4He.

The realization of an experimental facility for the measurement of cross sections of polarized nuclear fusion reactions with light nuclei is a complex project which involves various research groups. In particular the present project foresees the collaboration among four European Institutions, two of which are Italians.

The Petersburg Nuclear Physics Institute Academy of Sciences, Gatchina, Russia has the responsibility of the ion source for the incident beam as well as for the 100 keV ion accelerator and offers its experimental areas for the installation of the facility. The Institut fur Kernphysick of the Forshungzentrum laboratory of Juelich provides a Lambshift polarimeter for the measurement of the polarization of the beam and of the target jet. A big portion of these activities has already been financed.

The University of Ferrara has the responsibility of finalizing an atomic beam source for the target jet by upgrading the ABS already in operation at the Spinlab laboratory of the same University. The INFN Section of Ferrara will contribute to the assembly of the silicon detector and its relative read-out electronics. This will represent an additional application of the current development of the (anti)proton and deuteron silicon tracker in collaboration with Juelich for experiments with polarized beams.

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14 - Cost of the Research Units

nº	Associated Investigator	Cost A.1.1	Cost A.1.2	Cost A.2	Cost B	Cost C.1	Cost C.2	Cost D	Cost E	Cost F	Cost G	TOTAL
1.	*CONTALBRIGO Marco*	*55.635*	*0*	*48.800*	*62.661*	*0*	*0*	*32.700*	*18.990*	*0*	*0*	218.786
2.	*PAPPALARDO Luciano Libero*	*80.001*	*0*	*0*	*156.001*	*180.000*	*0*	*12.168*	*18.500*	*0*	*0*	446.670
	TOTAL	**135.636**	**0**	**48.800**	**218.662**	**180.000**	**0**	**44.868**	**37.490**	**0**	**0**	**665.456**

Legenda Cost item : <UL> <LI>**Cost A:** Personnel Costs <LI>**Cost B:** General costs <LI>**Cost C:** At least Three-year contracts (young-researchers) and International Well-Known researchers <LI>**Cost D:** Equipments costs <LI>**Cost E:** Travels & Subsistence cost <LI>**Cost F:** Consulting costs <LI>**Cost G:** Other costs

15 - General information and project duration

Research Program Duration	*48 Months*
Total Months/man dedicated to this Program	*178*
Total cost of the Program	*665.456*
Grant requested	*339.819*
Number of at least three-years contract (young researchers)	*1*
Total cost	*180.000*
Number of contract (well-known specialists)	*0*
Total cost	*0*

16 - Total cost of the project

nº	Associated Investigator	Grant requested	Young researchers	Well-known specialists	Total cost of the project
1.	*PAPPALARDO Luciano Libero*	*186.669*	*180.000*	*0*	*446.670*
2.	*CONTALBRIGO Marco*	*153.150*	*0*	*0*	*218.786*
	TOTAL	**339.819**	**180.000**	**0**	**665.456**

	Grant requested	Own funds	TOTAL
Research activities cost	*339.819*	*145.637*	485.456
At least Three-years contracts cost (young researchers)	*180.000*		180.000
Contracts cost (well-known specialists)	*0*		0
Total cost of the Program	*519.819*	*145.637*	665.456

Si ricorda che il cofinanziamento a carico del proponente deve essere pari al 30% del costo complessivo della proposta progettuale, detratti i costi dei contratti almeno triennali per giovani ricercatori e per ricercatori di chiara fama, che sono finanziati al 100%.

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Certifico, sotto la mia personale responsabilità, di aver ottenuto regolare autorizzazione dal rappresentante legale dell'ente di mia appartenenza, nonchè degli enti di tutte le altre Unità di Ricerca.

Data........... (inserita dal sistema al termine della redazione della domanda)