Abstract. Searches for non-paulian nuclear processes, i.e. processes normally forbidden by the Pauli–Exclusion–Principle (PEP) with highly radiopure NaI(Tl) scintillators allow the test of this fundamental principle with high sensitivity. Status and perspectives are briefly addressed.

1. Introduction
The exclusion principle was postulated by W. Pauli in 1925 to explain atomic spectra and regularities of the Periodic Table of the elements. In modern Quantum Field Theory the Pauli–Exclusion–Principle (PEP) is related to the spin statistics [1] and automatically arises from the anti-commutation property of the fermion creation and destruction operators. Despite the foundation of PEP lies deep in the structure of the Quantum Field Theory, a simple explanation is still missing. Thus, the exact validity of the PEP is still an open question in spite of all its known successes. In fact, the general principles of the quantum theory allow to go beyond the Bose and Fermi statistics and to also consider generalized statistics [2, 3, 4]. Many experimental tests of the PEP validity following the first pioneering experiments [5, 6] have been carried out so far by various approaches: i) searches for PEP-forbidden electronic states [7]; ii) searches for PEP-forbidden nuclear states [8]; iii) searches for PEP-forbidden electronic transitions [9, 10, 11, 12]; iv) searches for PEP-forbidden nuclear transitions [13, 14, 15, 16, 12]. It is worth noting that in 1980 Amado and Primako [17] criticized – on the basis of the assumption that the total Hamiltonian, describing the atoms, is completely symmetric in the electrons – the possibility of testing the Pauli principle by searching for PEP-forbidden transitions. However, their arguments can be evaded as demonstrated in refs. [18, 19]. In fact, in ref. [18] a theory has been developed where apparently non-paulian transitions could occur owing to the possible substructure of the electrons in composite models of quarks and leptons. In ref. [19] instead a theory, where extra dimensions could lead to apparent PEP violations, is discussed.

In the following we just introduce the present status of the search for non-paulian nuclear processes in highly radiopure NaI(Tl) and the related perspectives. In particular, since the nucleus is a fermion system, the nuclear structure is stable in case of an exact PEP, unless channels for strong, weak or electromagnetic decays are open. Thus, the usually considered
stable nucleus would not a priori be absolutely stable in case small violations of the PEP would exist and some exotic transitions (normally forbidden by PEP) in a stable nucleus may occur. As an example, adopting a nuclear shell description, one of the nucleons in a higher energy shell may fall into a lower energy state, normally occupied, and as a consequence another nucleon can acquire enough energy to reach the unbound region and to escape from the nucleus. The value of the average mixing probability of non-fermion statistics \( \delta^2 \) – which quantifies the possible PEP violations – can be derived considering the relation: 
\[
\Gamma = \Gamma^{(23\text{Na})} + \Gamma^{(127\text{I})} = \Gamma / \delta^2,
\]
where: i) \( \Gamma \) is the total width of the PEP violating nucleon transition; ii) \( \Gamma \) is the total width of the corresponding PEP allowed nucleon transition in case final states are empty, calculated for \( ^{23}\text{Na} \) and \( ^{127}\text{I} \) according to possible models for the momentum distribution functions of the nucleons in the bound state.

2. Present status in NaI(Tl) and the perspectives
Following previous studies [9, 14, 10], the present best limit on the investigation of non-paulian nuclear processes in NaI(Tl) scintillators has recently been set by means of the DAMA/LIBRA set-up at the Gran Sasso National Laboratory of the I.N.F.N. [12]; in particular, the non-paulian emissions of protons with \( E_p \geq 10 \text{ MeV} \) in \( ^{23}\text{Na} \) and in \( ^{127}\text{I} \) have been studied.

The performances of the highly radiopure DAMA/LIBRA set-up have been discussed in details in Ref. [20]; here we just remind that the sensitive part of the set-up is made of a \( 5 \times 5 \) matrix of highly radiopure NaI(Tl) crystal scintillators, 9.70 kg each one. In each detector two 10 cm long special quartz light guides act also as optical windows on the two end faces of the crystal and are coupled to two low background photomultipliers working in coincidence at single photoelectron level. The detectors are housed in a sealed low-radioactive copper box installed in the center of a low-radioactive Cu/Pb/Cd-foils/polyethylene/paraffin shield; moreover, about 1 m concrete (made from the Gran Sasso rock material) almost fully surrounds (mostly outside the barrack) this passive shield, acting as a further neutron moderator. The copper box is maintained in HP Nitrogen atmosphere in slightly overpressure with respect to the external environment; it is part of the threefold-levels sealing system which excludes the detectors from environmental air. A hardware/software system to monitor the running conditions is operative and self-controlled computer processes automatically control several parameters and manage alarms. Moreover, additional dedicated data taking optimized for the very high energy region can be performed as the running period of 23.7 days considered in ref. [12] to search for non-paulian proton spontaneous emission with energy above 10 MeV. It is worth noting that in that period one of the more external detectors was out of operation [20].

The process is investigated by analysing – in the MeV energy region – the events where just one detector fires (i.e. each detector has all the others as veto). The presence of identified alphas from residual U/Th contamination has also offered references for the energy scale [20]. The obtained results are discussed in details in ref. [12]. Here Table 1 just summarizes the experimental results, obtained with the DAMA/LIBRA detectors (24 in operation during the considered running period) by combining them in independent groups. The expected background events are also quoted; in this energy region the background is essentially due to very high energy muons possibly surviving the mountain. Generally the very high energy muons give rise in DAMA/LIBRA to events, in which several detectors fire, and thus they can be easily identified and are not competing background in the search for the PEP violating processes. Thus, only muons, impinging the sensitive volume of the set-up with a direction that forbids them to hit more than one detector, can play the role of background for the processes searched for and have to be considered. Therefore, a suitable MonteCarlo simulation [12] has been realized on the basis of the features of the DAMA/LIBRA set-up [20], of the vertical muon intensity distribution and of the Gran Sasso rock overburden map of ref. [21]. From the final combined result given in Table 1: \( \lambda \leq 1.63 \times 10^{-33} \text{ s}^{-1} \), the limit on the non-paulian nuclear transition width has been.
Table 1. Comparison between the number of background events expected above 10 MeV from high energy muons surviving the mountain and the number of measured events, considering various groups \((J)\) of detectors in the experimental set-up (5 rows by 5 columns detectors matrix, but an external detector out of operation); see text. Upper limits on the rates of non-paulian processes leading to the emission of protons with \(E_p \geq 10\) MeV are also reported for the various configurations; the final combined result is given. See ref. \[12\]

| Group \((J)\) of considered detectors | Corresponding exposure \((N_J t)\) (nuclei \(\times\) s) | Expected background events \((b_J)\) | Measured events \((n_J)\) | Upper Limit on \(\lambda\) \((90\% \text{ C.L.})\) \((s^{-1})\) |
|---------------------------------------|-------------------------------------------------|----------------------------------|----------------|----------------------------------|
| Just the 4 detectors at corners \((I)\) | \(3.2 \times 10^{32}\) | 12.1 | 11 | \(1.99 \times 10^{-32}\) |
| Just the remaining 6 detectors in the upper and lower rows \((II)\) | \(4.8 \times 10^{32}\) | 8.7 | 6 | \(9.33 \times 10^{-33}\) |
| Just the 14 central detectors \((III)\) | \(1.1 \times 10^{33}\) | 2.2 | 0 | \(2.06 \times 10^{-33}\) |
| Just the 9 core detectors \((IV)\) | \(7.2 \times 10^{32}\) | 0.057 | 0 | \(3.19 \times 10^{-33}\) |
| Combined analysis \((I+II+III):\) | | | | \(1.63 \times 10^{-33}\) |

derived to be: \(\Gamma = \Gamma^{(23)Na} + \Gamma^{(127)I} = h\lambda \leq 1.1 \times 10^{-54}\) MeV \((90\% \text{ C.L.})\). It is an improvement of about a factor 3 with respect to the limits previously available \[13, 14\]. From this value – considering the same nuclear Physics frameworks as in ref. \[14\] – a cautious estimate of the average probability, \(\delta^2\), which quantifies the possible PEP violations, has been derived to be: \(\delta^2 \leq 3 - 4 \times 10^{-55}\), and a lower limit on the mean life for non-paulian proton emission has also been set: \(\tau_{Na} \geq 2 \times 10^{29}\) yr and \(\tau_I \geq 2.5 \times 10^{25}\) yr. These latter limits improve those previously available \[13, 14\].

Let us now discuss the perspectives to further investigate non-paulian nuclear transitions in DAMA/LIBRA with dedicated long data taking optimized for very high energy. In fact, it is worth noting that a much larger sensitivity can be obtained by suitably increasing the dedicated collected exposure, considering the high self-veto efficiency of the 9 inner core detectors. Fig. 1

Figure 1. Background energy distributions expected for different sets of DAMA/LIBRA crystals considering the events where just one detector fires. Case a): average contribution of the 10 upper and lower crystals in the 5 \(\times\) 5 matrix. Case b): average contribution of the remaining 15 crystals. Case c) average contribution of the 9 inner crystals.
shows the background energy distributions expected for different sets of DAMA/LIBRA crystals considering the events where just one detector fires. In particular, it is shown the average background contribution of: i) the 10 upper and lower crystals in the $5 \times 5$ matrix (case a); ii) the 15 central crystals (case b); iii) the 9 inner detectors (case c).

It is worth noting that the maximum expected energy release in the PEP violating nuclear transition can be written as: $E_{\text{max}} = V - B_N$, where $V$ is the nuclear potential and $B_N$ is the nucleon binding energy. Considering $V \simeq 40$ MeV and $B_N \simeq 6 - 12$ MeV for $^{23}$Na and $^{127}$I, the maximum energy release is expected to be below $\sim 34$ MeV [13]. As it can be inferred from the case c) of Fig. 1, less than 1 background event is expected in the 9 NaI(Tl) detectors in the inner core of DAMA/LIBRA during $\sim 1000$ days exposure in the 10 – 35 MeV energy interval. This can allow to explore the probability of admixed symmetric component at level of $\delta^2 \leq 1 - 2 \times 10^{-56}$ (at 90% C.L.). Therefore in $\sim 3$ years exposure the sensitivity of DAMA/LIBRA to non-paulian nuclear transitions in $^{23}$Na and $^{127}$I can be improved of about one order of magnitude without any simulated muon background subtraction.

3. Conclusions
The highly radiopure DAMA/LIBRA set-up [20, 22, 12] is in operation at the Gran Sasso National Laboratory of the INFN; it has a sensitive mass of about 250 kg of highly radiopure NaI(Tl). By means of this set-up new searches for non-paulian nuclear processes, i.e. processes normally forbidden by the Pauli exclusion principle, have been carried out achieving the presently most stringent results in $^{23}$Na and $^{127}$I. The possibility to achieve significantly increased sensitivity with new long-term optimized data taking has been introduced.

For completeness, we remind that DAMA/LIBRA has also investigated with a very large exposure PEP violating electron transitions in Iodine atoms in ref. [12].

References

[1] W. Pauli, Phys. Rev. 58 (1940) 716.
[2] A. M. Messiah and O. W. Greenberg, Phys. Rev. 136 (1964) B248.
[3] O. W. Greenberg, Phys. Rev. Lett. 64 (1990) 705; R. N. Mohapatra, Phys. Lett. B 242 (1990) 407; O. W. Greenberg and R. C. Hilborn, Fund. Phys. 29 (1999) 397.
[4] G. Gentile, Nuovo Cimento 17 (1940) 493; H. S. Green, Phys. Rev. 90 (1953) 270; A.Yu. Ignatiev and V.A. Kuzmin, Sov. J. Nucl. Phys. 46 (1987) 786; V. N. Gavrin, A. Yu. Ignatiev and V. A. Kuzmin, Phys. Lett. B 206 (1988) 343; O. W. Greenberg and R. N. Mohapatra, Phys. Rev. Lett. 59 (1987) 2507.
[5] M. Goldhaber and G. Goldhaber, Phys. Rev. 73 (1948) 1472; E. Fischbach, T. Kirsten, and O. A. Schaeffer, Phys. Rev. Lett. 20 (1968) 1012; B. A. Logan and A. Ljubicic, Phys. Rev. C 20 (1979) 1957.
[6] F. Reines and H. W. Sobel, Phys. Rev. Lett. 23 (1974) 954.
[7] V. M. Novikov et al., Phys. Lett. B 240 (1990) 227; K. Deilamian et al., Phys. Rev. Lett. 74 (1995) 4787; A. S. Barabash, et al., JETP Lett. 68 (1998) 112; D. Javorsek II et al., Phys. Rev. Lett. 85 (2000) 2701.
[8] E. Nolte et al., J. Phys. G 17 (1991) S355.
[9] H. Ejiri et al., Nucl. Phys. B (Proc. Suppl.) 28A (1992) 219.
[10] P. Belli et al., Phys. Lett. B 460 (1999) 236.
[11] S. Bartalucci et al., Phys. Lett. B 641 (2006) 18; E. Milotti et al., Int. J. Mod. Phys. A 22 (2007) 242.
[12] R. Bernabei et al., Eur. Phys. J. C 62 (2009) 327.
[13] H. Ejiri and H. Toki, Phys. Lett. B 306 (1993) 218.
[14] R. Bernabei et al., Phys. Lett. B 408 (1997) 439.
[15] R. Arnold et al., Eur. Phys. J. A 6 (1999) 361; Nucl. Phys. B (Proc. Suppl.) 87 (2000) 510.
[16] H. O. Back et al., Eur. Phys. J. C 37 (2004) 421.
[17] R. D. Amado and H. Primako, Phys. Rev. C 22 (1980) 1383.
[18] K. Akama et al., Phys. Rev. Lett. 68 (1992) 1826.
[19] see e.g. O. W. Greenberg and R. N. Mohapatra, Phys. Rev. D 39 (1989) 2032.
[20] R. Bernabei et al., Nucl. Instr. & Meth. A 592 (2008) 297.
[21] M. Ambrosio et al, Phys. Rev. D 52 (1995) 3793.
[22] R. Bernabei et al., Eur. Phys. J. C 56 (2008) 333.