PANTHEON: TOWARDS HIGH-PRECISION TESTS OF THE PAULI EXCLUSION PRINCIPLE IN NUCLEAR REACTION AS A TESTBED OF THEORIES BEYOND THE STANDARD MODEL*

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The PANTHEON project aims to test the Pauli Exclusion Principle (PEP) in nuclear reactions by searching for nuclear transitions prohibited by PEP in processes respecting the Messiah–Greenberg super-selection rule. The project aims at using the proton beam from the 3.5 MV Singletron accelerator of the Bellotti facility located at the Gran Sasso Underground Laboratory, to perform a measurement based on a test setup able to disentangle protons coming from the PEP-prohibited processes. The goal is to prepare a dedicated setup for future measurements to improve by orders of magnitude the limit on PEP violation established in previous studies and challenge theories beyond the Standard Model at a precision level presently unattained.

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1. Introduction

The PANTHEON (towards high-precision tests of the PAuli exclusion principle in Nuclear reaction as a testbed of THEories beyONd the standard model) project plans to test our understanding of the fundamental symmetries of nature, particularly the permutation symmetry of identical particles and the implications of the Pauli Exclusion Principle (PEP) in nuclear reactions. The Pauli Exclusion Principle, deeply rooted in the spin-statistics theorem, plays a pivotal role in our understanding of natural phenomena, ranging from the stability of atoms and nuclei to the structure of neutron stars. Despite its fundamental importance, the lack of an intuitive explanation for PEP, as highlighted by Pauli himself in his Nobel Lecture in 1946 [1], underscores the need for further rigorous testing and exploration. In this context, the search for potential small violations of the Pauli Exclusion Principle assumes paramount significance, akin to the searches for CPT and Lorentz symmetries violations. Violations of CPT, Lorentz symmetry, but also the possible existence of extra-dimensions, non-commutative space-time geometries and violation of locality [2] are in fact embedded in various beyond the Standard Model scenarios, such as quantum gravity models [3, 4].

The approach used to detect PEP violations generally revolves around experimentally investigating atomic and nuclear transitions that are forbidden by PEP. Importantly, these transitions exhibit distinct experimental signatures that can be accurately calculated, since the energy difference with respect to the standard transitions is due to the screening effect of the additional electron or nucleon in the final state.

The Messiah–Greenberg (MG) super-selection rule [5] states that a system would not manifest a violation of PEP unless a new particle is introduced in the system from outside. We call the framework an *open system* if the MG super-selection rule is enforced at the experimental level or a *closed system* if not, noting that experimental techniques such as those related to the stability of the atoms or nuclei belong to a closed system framework.

The classification of experiments based on their adherence to the MG super-selection rule, which dictates the conditions under which a system could manifest a violation of PEP, provides a framework for understanding and categorizing the search for violations of PEP, as outlined by Elliot [6]:

— Type I interactions are between a system of fermions and a fermion that has not previously interacted with any other fermions.

— Type II interactions are between a system of fermions and a fermion that has not previously been in the given system.

— Type III interactions are between a system of fermions and a fermion within that given system.

Type I experiments involve, for example, a freshly produced fermion, such as an electron from a beta decay; conversely, type III experiments correspond to closed systems as outlined above. In type II, which is the focus of this project, a fermion is introduced from outside a system; this can be achieved in the context of atomic physics with an electric current, as done at the Gran Sasso National Laboratories (LNGS) by the VIP Collaboration [7–10]. In the context of nuclear physics, an MG-complying, PEP-violating transition can be searched for by introducing inside the nucleus an external "proton current" through the bombardment of a target material by a proton beam. This was pioneered in 1990 using a CN Van de Graaff accelerator providing a 3 MeV proton beam directed on a thin carbon target [11]. In that case, the signature of PEP violation searched for was an exoergic (p, p') nuclear transition, as illustrated in figure 1. The energy of the p' outgoing proton was calculated to be between 5 and 28 MeV. Additionally, investigations were conducted on the alpha final state.

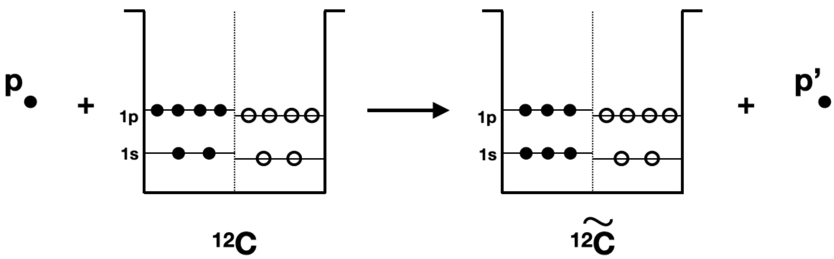

Fig. 1. The PEP-violating process considered in [11] in the proton exoergic (p, p') final state. A ^{12}C target is bombarded by 3 MeV protons, p (left). The PEP violation occurs, emitting a proton of energies between 5 and 28 MeV, p', and leaving a non-Paulian nucleus $\widetilde{^{12}\mathrm{C}}$, right. In the schemes, the $1s$ and $1p$ levels for protons (solid circles) and neutrons (empty circles) are shown.

Based on their result, no evidence of the PEP-violation signature was found, and a limit to the PEP violation with these nuclear processes was set, expressed as a limit of cross-section ratios between the Pauli principle violating processes and the elastic scattering of 1.3×10^{-13}.

The PANTHEON project seeks to build on previous experiments and pioneer new methods to test PEP in nuclear reactions. The project's scientific motivation is underpinned by the quest to challenge theories beyond the Standard Model at a precision level presently unattained. The upcoming test measurement at the Bellotti facility in 2024 represents a crucial step in the project's pursuit of improving the limit on PEP violation established in 1990.

2. Project description

The PANTHEON project aims at setting the strongest bounds on the Pauli Exclusion Principle (PEP) violation in nuclear reactions, focusing on the exoergic inelastic (p, p') scattering on carbon. The project will commence with a test setup, paving the way for a dedicated experimental effort in the coming years. The experimental setup will make use of the 3.5 MV Singletron accelerator of the Bellotti Ion Beam Facility [12], utilizing H^+ ions at the maximum allowed beam intensity. The key elements of the setup are depicted in figure 2, which includes a schematic view of the test setup and a 3D render showing the support element.

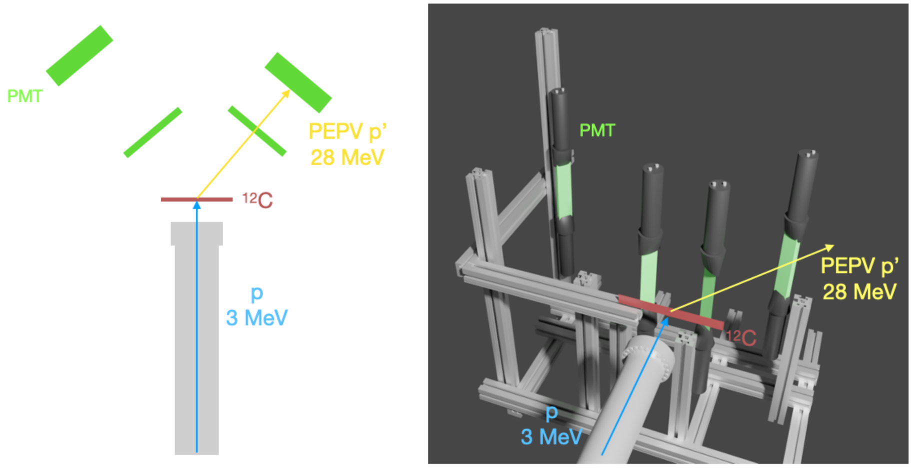

Fig. 2. Left: Schematic view of the test setup. Right: The 3D render showing the support element.

The 3.5 MV Singletron accelerator will provide a proton beam up to 3 MeV (indicated by the blue arrow) which will impinge on a 40 μm thick ^{12}C target (9 mg/cm^2) inside a scattering chamber (not shown for clarity) in vacuum to minimize particle losses and multiple scatterings. The maximum current that the accelerator can provide is 1 mA. The signature of exoergic (p, p') PEP-violating inelastic scattering is an outgoing proton of higher energy, up to 28 MeV. In the initial test setup, this will be detected by a telescope of two plastic scintillators read out by a couple of photomultiplier tubes (PMTs) assuring fast and reliable timing. In the case of PEP violation, other channels could open, such as (p, γ), however in this first test run, we focus on the measurement of the (p, p') channel, also for comparison with the previous work (with the aim to complement the setup for spectroscopy in the future). The scintillators are placed at 50° and −50° with respect to the beam axis to provide higher total acceptance and characterize possible systematic effects. Since the outgoing proton from PEP-violating nuclear reactions would have a higher energy with respect to the elastically scattered ones, a key experimental requirement is the reconstruction of its energy.

This is achieved via a twofold approach. First, the light yield of the scintillators can be used to achieve a measurement of the ΔE energy in the sensitive volume. For this reason, we will use for the first scintillator a thickness of about 1 mm. Figure 3 shows the energy deposition of protons inside the plastic scintillators as a function of their thickness.

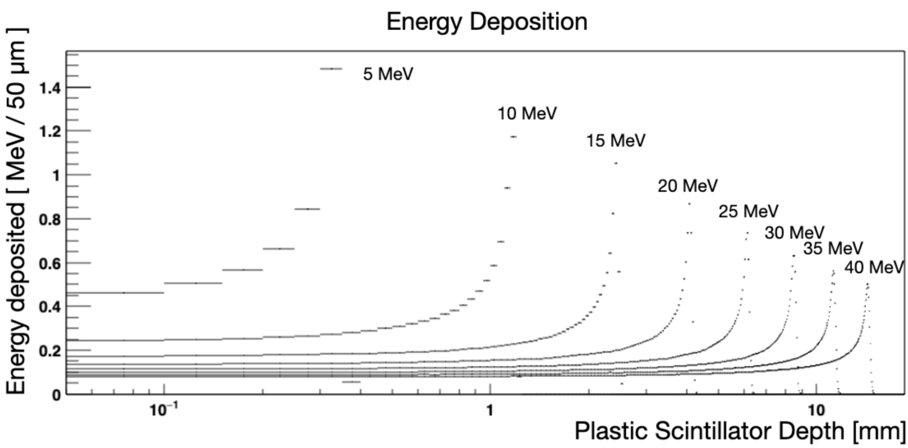

Fig. 3. Energy deposition in plastic scintillator as a function of the depth for different energies of an incoming proton.

Employing a secondary scintillator with a thickness of approximately 10 mm, even at the highest proton energies reaching up to 28 MeV in the PEP-violating process within carbon (further theoretical advancements will be explored within PANTHEON), proves adequate for entirely halting the proton within the active volume. This allows for a direct measurement of the total energy, provided the sufficient characterization of the material budget from the interaction point.

To provide redundancy and more accurate measurement of the energies, the time of flight could effectively be used to derive the total energy of the protons. For this reason, we foresee one arm with a distance of 50 cm (corresponding to about 6 ns for 28 MeV protons) between the scintillators, well within the mean timer resolution of typical scintillator systems (see *e.g.* [13] in the framework of the SIDDHARTA-2 Collaboration, where the mean timer resolution was characterized to be of about 140 ps). To achieve a higher acceptance, the second arm can be arranged with the scintillators closer to each other, trading off energy resolution.

PANTHEON's experimental approach is poised to improve the existent limit on PEP violation by about one order of magnitude, setting the stage for future dedicated measurements with setups including searches for gamma radiation emitted in PEP-violating transitions in coincidence with the protons. PANTHEON will lay the groundwork for tests of theories beyond the Standard Model, which predict the PEP violation in nuclear reactions.

3. Conclusions and outlook

The Pauli Exclusion Principle is a key ingredient of modern quantum physics, with implications from the stability of matter to neutron stars. Beyond the Standard Model theories, especially connected with the nature of spacetime, could entail a violation of the PEP, albeit small. So far, a large number of the experimental efforts have focused on searches which do not comply with the MG super-selection rule. Within the MG, systematic searches have been performed under the VIP Collaboration at LNGS, in the context of atomic physics. In nuclear physics, instead, there has been a lack of progress in the last 30 years, leaving behind the investigation of PEP violation with nucleons. With PANTHEON, we plan to continue the scrutiny of PEP violation in nuclear reactions, leveraging the low-background environment and high-intensity beam provided by the Bellotti Ion Beam Facility at the Gran Sasso National Laboratories.

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