Search for New Physics beyond the Standard Model with precision measurements in nuclear beta decays

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I. Introduction

Nuclear Physics has played a major role in establishing the laws of physics at the most fundamental level and in shaping the Standard Model of elementary particles (SM). Notable examples include the discovery of maximal violation of spatial inversion symmetry, *P*, the left-handed vector axial-vector (*V-A*) nature of the weak interaction and the conservation of the vector current. Today, the SM still leaves open questions such as the masses of neutrinos, the nature of dark matter, the baryon asymmetry etc… and most efforts are dedicated to the search for New Physics (NP), *i.e* observations that would reveal deviations from the SM predictions. This search is a strong motivation for experiments carried out both at the high energy frontier, with the most powerful particle colliders, and at the precision/intensity frontier, in low energy processes such as β decay. A recent theoretical approach, based on effective field theories, enables a relevant comparison between results obtained at low and high energies highlighting their complementarity at a given level of precision.

The development of new and always more advanced technologies suggests that unprecedented precisions should be reached in future low energy measurements, which require the control of systematic effects at equivalent levels of precision. Analysis and interpretation of results must also include higher order effects which have thus to be determined or computed with the appropriate accuracy.

In this context, key experiments, which could be performed during the next decade with specific nuclei and using well defined experimental methods, can be identified. Theoretical efforts should also be sustained. The projects and experiments carried out by the laboratories of IN2P3 involved in the field focus on the 3 following specific topics discussed in the next sections:

- The search for exotic currents beyond the *V-A* theory
- The search for new sources of *CP* violation
- The conservation of the vector current and the unitarity of the CKM matrix.

II. Search for exotic interactions in nuclear beta decay

In the search for exotic couplings involving a scalar (*S*) or tensor (*T*) structure of the weak interaction, high-precision measurements of β energy spectra and of $\beta-\nu$ correlation parameters in light nuclei and in the neutron decays have been identified as most promising to reach comparable or higher sensitivities than LHC experiments. These measurements give access to the Fierz interference term, *b*, whose determination with a precision better than 10^{-3} would probe NP at an energy scale of ~10 TeV. More than ten projects are currently under development worldwide to perform, within the coming decade, $\beta-\nu$ correlation measurements at the per mil precision level. Four other projects, with a similar goal, focus on the direct extraction of the Fierz term, *b*, from the measurements of β energy spectra. Teams from IN2P3 are involved in two of these projects: **WISArD** ("**W**eak **I**nteraction **S**tudies with ^{32}**Ar D**ecay") and **b-STILED** ("**b**: improved **S**earch for **T**ensor **I**nteractions in nuc**L**ear b**E**ta **D**ecay"). Some are also involved in the measurement of the $\mathcal{F}t$ values of superallowed $0^+ \rightarrow 0^+$ β decays which presently provide the best constraints on left-handed scalar contributions (see section IV).

WISArD aims at the improvement, by a factor of 5 to 10, of the present limits on *b* inferred from correlation measurements in pure Fermi decays. It is based on the measurement of the kinetic energy shift of protons emitted in parallel or anti-parallel directions with respect to the positron in the decay of

^{32}Ar. A proof-of-principle experiment performed at ISOLDE/CERN already provided simultaneous measurements for superallowed $0^+ \rightarrow 0^+$ and Gamow-Teller transitions followed by proton emission. The first results, obtained with a precision at the percent level, have shown a significant gain in sensitivity on *b* (about a factor of 5) and a limited contribution of the main sources of systematic errors. A dedicated and much improved setup funded by the ANR (620k€) and the Belgian FWO (450k€) is presently under development. The primary goal is to reach the per mil precision level in the five coming years with several experimental campaigns at ISOLDE/CERN. With the present ^{32}Ar production at ISOLDE and the future detection setup, realistic projections show that this goal could be achieved within a two-week period of beam time. As of 2024, further improvements will be pursued at the GANIL DESIR facility, with radioactive beams of higher intensity.

The b-STILED project, based on the "hermetic detector" technique, will measure the shape of the β energy spectrum in the decay of ^6He. For this pure Gamow-Teller transition, tensor interaction would manifest through a non-zero Fierz interference term *b* and generate a small differential distortion of the β spectrum, driven by the factor m_e/E_e. The aim of the project is to measure *b* at a per mil precision level within the 5 coming years. The dominant source of uncertainty for such measurements usually comes from the backscattering of β particles leading to a reduced deposited energy in the detectors. This backscattering contribution can be eliminated by using a decay source fully enclosed in the detector geometry. To do so, the b-STILED project will follow two different methods. The first one consists in the implantation of ~300 MeV ^6He ions in a scintillator crystal at depths that are larger than the range of the β particles. This technique was already demonstrated at Michigan State University. First results are expected soon, with precisions of a few per mil on *b*. The second method makes use of low energy (~20 keV) ^6He ions periodically implanted at the surface of a scintillator detector. After each implantation, an identical detector moves in front of the implantation region and closes the detection volume prior to starting the β spectrum measurement. Both methods are complementary as they are affected by different sources of systematic errors. The project will be carried out at GANIL, where ^6He ion production is the highest worldwide and where pure ^6He beams can be available both at high (LISE) and low energy (LIRAT & DESIR). The response function of the detection setups is another critical point that will be tackled using independent calibration measurements with the 0.2-3.8 MeV electron source ATRON located in Cherbourg. Sources of funding for the project will be sought through the ANR, the Region Normandie, and the IN2P3.

III. Search for CP violation in nuclear beta decay

Why are we living in a world of matter? What is the reason for the strong matter – antimatter asymmetry observed in the Universe?

In 1967, A. Sakharov expressed the 3 conditions which should be fulfilled for the baryogenesis process, giving rise to large matter – antimatter asymmetry. These conditions are: (i) a large *C* and *CP* violation; (ii) a violation of the baryonic number, (iii) a process out of thermal equilibrium. At high energy, *CP* violation has been observed in the decay of the K and B, and lately D^0 mesons. *CP* violation is incorporated in the SM via the quark mixing mechanism, but at a level which is not sufficient to explain the hegemony of matter during baryogenesis. A much larger *CP* violation has yet to be discovered, out of reach from colliders, but for which low energy observables, like the *D* and *R* triple correlations appearing in the mirror decay of polarized nuclei and Electric Dipole Moments, are sensitive probes. The *D* correlation offers the possibility to search for new *CP*-violating interactions in the SM *V-A* theory framework and in a region that is less accessible by EDM searches, in particular via the Leptoquark model. Leptoquarks are gauge bosons coupling leptons and quarks which appear in many extensions of the SM. Their decay out of thermal equilibrium in the frame of Grand Unified Theories came rather evidently as the first hypothesis for the baryon and lepton number non conservation. As such, Leptoquarks still play a peculiar role among various baryogenesis models. Remarkably, they have been lately invoked to explain recently observed flavor non-conservation in the decay of B mesons.

The "**M**atter's **O**rigin from **R**adio**A**ctivity" (**MORA**) project aims at measuring the *D* correlation at the 10^{-5} level, i.e. a factor of ~10 better than the present limit (*D* (neutron decay) $\leq 2\times10^{-4}$). It is making use of an innovative polarization technique, which combines the high efficiency of ion trapping with the one of laser orientation. The proof-of-principle of this technique is the main motivation of the first tests with $^{23}Mg^{+}$ ions at the University of Jyväskylä, which are foreseen in the coming years (2020-2021). The efforts will be then devoted to the first *D* correlation measurement (2022-2024), still in Jyväskylä, with a goal in sensitivity of ~5×10^{-4}, which is better than the present constraint from nuclear beta decay ($D_{19Ne} \leq 6\times10^{-4}$). As of 2024, the DESIR facility will offer a perfect environment for MORA: DESIR will benefit from both the intense beams from SPIRAL 1 and the exotic beams from S3-LEB. DESIR will be equipped by state-of-the-art purification tools, such as the High Resolution Separator (HRS) and a MR-ToF-MS. The lasers presently missing at SPIRAL 1 for the proof-of-principle of the polarization technique will be available from the LUMIERE setup. With the intensity of ^{23}Mg available at SPIRAL 1, the 10^{-5} precision level will become accessible.

In *D* correlation measurements, the window to search for NP will eventually be limited by the level at which the effects of electromagnetic Final State Interaction (FSI), which mimic the existence of a non-zero correlation, can be calculated. The FSI effects have never been observed so far at the present level of precision on *D.* Such effects are typically of the order of 10^{-4} to 10^{-5} depending on the system, and have been recently calculated to an absolute accuracy of 10^{-7} for the neutron. D_{FSI} values of the order of 1.1×10^{-4} and -0.3×10^{-4} can be estimated for ^{23}Mg and ^{39}Ca, respectively. If *CP* violation is not clearly highlighted in the *D* (^{23}Mg) measurement, then this measurement would become the first relevant test of the accuracy of such theoretical estimates. The shorter half-life of ^{39}Ca and its reduced FSI effects make it an ideal counterpart of ^{23}Mg but it is presently not produced at the required rate at any facility. Efforts should thus be sustained, in the second part of the 20's, to provide such a beam at either S3 or SPIRAL 1. NP would remain accessible up to a precision level of 10^{-6} corresponding again to the sensitivity level to D_{FSI} in the case of ^{39}Ca.

The MORA project is presently funded by Region Normandie, mainly for equipment and postdoc (630k€ shared between GANIL and LPC Caen). As of 2020, an additional support from ANR will become available for postdocs, PhD student and missions (440k€). LPT Orsay joined the ANR project to carry out theoretical studies related to MORA. LPT Orsay will revisit the sensitivity of the *D* correlation to NP in a broader context than what was envisaged so far, and will revise the FSI effects in nuclear decays to compute their contribution in *D* at a relative precision level of 1%

IV. Conservation of the vector current and the unitarity of the CKM matrix

The building blocks of the SM are (i) 12 fermions, or elementary matter particles, - six quarks and six leptons, (ii) the exchange bosons - fundamental force carriers - the gluons, the Z and $W^{\pm}$ bosons and the photon, mediating strong, weak and electromagnetic interactions, and (iii) the Higgs boson. In this model, the fundamental quarks, the “weak eigenstates” of the quarks, are a mix of the “mass eigenstates”. This mixing between 3 generations of quarks is described by the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix. The unitarity of the 3x3 CKM matrix would put stringent limits on possible physics beyond the SM: existence of a fourth generation of quarks, right-handed currents, leptoquarks and others.

The largest and best known element of this quark mixing matrix is the upper row V_{ud} element. It can be determined by three different measurements: the pion beta decay ($\pi^{+} \rightarrow \pi^{0} + e^{+} + \nu$), mirror β decays including neutron decay, and $0^{+} \rightarrow 0^{+}$ β decays. By far the best precision is reached by the $0^{+} \rightarrow 0^{+}$ decays, followed by mirror and pion decays with about a factor of ten less precision.

In the case of nuclear $0^{+} \rightarrow 0^{+}$ beta decays, the *ft* value for a given transition is first deduced from the measured decay Q value and partial half-life for the super-allowed Fermi (vector) decay branch. For mirror decays, in addition the Gamow-Teller-to-Fermi mixing ratio has to be determined. Then the corrected (or absolute) $\mathcal{F}t$ value for each transition is obtained by taking into account small corrections due to isospin-symmetry breaking and radiative effects. The advantage of nuclear beta decay is that a set of different nuclei can be used: At present, fifteen $0^{+} \rightarrow 0^{+}$ β decays in nuclei with Z between 6 and 37 have been measured with a precision of the order of 0.1%, while 6 mirror decays including the neutron are known with a good precision. This offers the possibility to test the conserved vector current

(CVC) hypothesis: the absolute $\mathcal{F}t$ value for a given set of transitions, for example various $0^+ \rightarrow 0^+$ transitions among T=1 states, should be constant. However, this necessity to account for small theoretical corrections introduces today the largest uncertainties for the average $\mathcal{F}t$ value. The latter is required to extract the vector coupling constant G_V and eventually the V_{ud} matrix element.

Presently CVC is verified in $0^+ \rightarrow 0^+$ β decays at a level of several 10^{-4}. Additional measurements and theoretical work on the corrections will still improve this limit and/or lead to a somewhat different average $\mathcal{F}t$ value. The following research directions towards the determination of V_{ud} have to be pursued:

- Precise measurements of other $0^+ \rightarrow 0^+$ β decays to test CVC over a larger range of nuclei:
  - studying the decay of more exotic nuclei (e.g. T_z= -2 emitters);
  - extending the range of Z of nuclei by studying heavier emitters along the N=Z line;
  - improving the branching ratios of known transitions from T_z= -1 emitters
- Development of accurate nuclear models for the evaluation of theoretical isospin-symmetry breaking corrections δ_c , in particular for heavier and more exotic nuclei;
- More precise characterization of the light $0^+ \rightarrow 0^+$ β decays (^{10}C and ^{14}O) which allow an efficient search for scalar current contributions to the weak interaction, in complementarity to the WISArD project (see section II).

The lightest nuclei, ^{10}C and ^{14}O, are produced already today with sufficient intensities (about 10^3 pps or more) at SPIRAL1 for the experimental program proposed here. The most exotic and in particular the heaviest (A>50) nuclei will be produced in ample amounts with the new S3-LEB facility. For example, N=Z nuclei up to ^{94}Ag will be produced with intensities needed for this physics program (>10^3 pps). This will enable testing CVC over a much wider range in Z than today. These experiments can be performed at the DESIR facility which will allow preparing ultra-pure samples of all the nuclei of interest with the HRS or PIPERADE. Mass (or Q value) measurements can be performed with MLLTRAP, whereas half-lives and branching ratios can be obtained with set-ups including β-particle and γ-ray detectors.

Similar measurements can also be performed with mirror β decays. All mirror decays from the neutron up to ^{99}In can be used. For many of these decays the Q value, the half-life and the branching ratio are “relatively easy” to measure with the same technique and the same set-ups as for $0^+ \rightarrow 0^+$ β decays. The most difficult part is the determination of the Gamow-Teller-to-Fermi mixing ratio, which has to be extracted from a β-ν angular correlation or β asymmetry measurement. MORA will be the set-up of choice at DESIR. Basically all equipment needed for this program will be available at DESIR.

As for the theoretical corrections mentioned above, work is already ongoing within the present collaboration to develop models and tools complementary to those used presently and to extend the range of nuclei for which these theoretical corrections will be available.