Search for New Physics beyond the Standard Model with precision measurements in nuclear beta decays: a research field @ GANIL

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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, a large part of which could be performed during the next decade with specific nuclei and using well defined experimental methods, can be identified. The projects and experiments carried out by French laboratories involved in the field focus on the three specific topics summarized below[1].

I. 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 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. French teams are involved in two projects: WISArD ("Weak Interaction Studies with ^{32}Ar Decay") and b-STILED ("b: improved Search for Tensor Interactions in nucLear bEta Decay"). 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 III).

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**. The first results of a proof-of-principle experiment performed at ISOLDE/CERN 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 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. **As of 2024, further improvements will be pursued at the GANIL DESIR facility, with different radioactive beams (^{20}Mg, ^{24}Si, ^{28}S instead of ^{32}Ar presently at ISOLDE) and of higher intensity.**

[1] Details can be found in the contribution to the IN2P3 prospectives 2020.

The b-STILED project, based on the "hermetic detector" technique, will measure the shape of the β energy spectrum in the decay of ^{6}He. The aim of the project is to determine b_{GT} at a per mil precision level within the 5 coming years. To eliminate the β backscattering contribution, the project will follow two different methods. The first one consists in the implantation of ~300 MeV ^{6}He ions in a scintillator crystal at depths that are larger than the range of the β particles. The second method makes use of low energy (~20 keV) ^{6}He 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 ^{6}He ion production is the highest worldwide and where pure ^{6}He beams can be available both at high (LISE) and low energy (SPIRAL & DESIR).**

II. Search for CP violation in nuclear beta decay

In our Universe, matter has overcome antimatter and a condition required to explain this phenomenon is the violation of *CP* symmetry. Present contributions accounted for in the SM are 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* triple correlations appearing in the mirror decay of polarized nuclei is a sensitive probe. The MORA project (Matter's Origin from RadioActivity) aims at measuring this triple *D* correlation at the 10^{-5} level, i.e. a factor of ~10 better than the present limit. 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 and the first *D* correlation measurements will be performed at the University of Jyväskylä with **^{23}Mg^{+}** ions (2022-2024). **As of 2024, the DESIR facility should offer a perfect environment for MORA**: **DESIR** will benefit from both the more intense beams from **SPIRAL 1** and the exotic beams from **S3-LEB**, allowing to reach the 10^{-5} precision level. The shorter half-life of **^{39}Ca** and its reduced final state interaction effects make it an ideal counterpart of ^{23}Mg but it is presently not produced at the required rate at any facility. **Efforts are thus required, in the second part of the 20's, to provide such a beam at either S3 or SPIRAL 1.**

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

In the SM, the "weak eigenstates" of the quarks are a mix of the "mass eigenstates". This mixing between 3 generations of quarks is described by the CKM matrix. The unitarity of this 3x3 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 the CKM matrix is the upper row V_{ud} element, for which the best precision is by far reached thanks to corrected $\mathcal{F}t$ values of fifteen $0^{+} \rightarrow 0^{+}$ decays. This requires high precision measurements of masses, half-lives and branching ratios, and computation of different theoretical corrections which presently limit the final uncertainty on the $\mathcal{F}t$ values.

Additional measurements in heavier nuclei (^{66}As, ^{70}Br, ^{78}Y,…) are thus needed, not only to improve and better control theoretical corrections, but also to enlarge the range of nuclei for which the CVC hypothesis is presently verified at a level of several 10^{-4}. Moreover a better characterization of the lightest decays (^{10}C and ^{14}O) is essential to allow an efficient search for scalar current contributions to the weak interaction, in complementarity to the WISArD project (see section I). Finally similar measurements can also be performed with mirror β decays (^{23}Mg, ^{33}Cl, ^{37}K,…) to provide stringent constraints on the models used to compute the theoretical corrections.

Experiments were performed so far in various facilities providing the beams of interest with sufficient intensities and adapted conditions (JYFL, ISOLDE, GANIL, TRIUMF,…). **As of 2024, DESIR should offer a unique opportunity, hosting all the devices needed and providing all the nuclei of interest (produced by SPIRAL1 and S^{3}-LEB).** This ideal situation would allow the allocation of long beam periods by sharing the beam between several devices or using different beams in parallel.

IV. Conclusions: assets of GANIL and requirements

A large part of experiments presented here are currently not carried out at GANIL but in other facilities, outside France. However, the same projects have foreseen to come back home because GANIL should offer unique conditions allowing hopefully their achievement during the next decade, at the targeted precision level. This statement assumes that, on one hand, the existing GANIL will continue to deliver the SPIRAL1 beams, some with the highest intensities worldwide (with continuous efforts to provide new radioactive ion beams) and, on the other hand, the DESIR facility[2] will be effectively built. This low energy facility of second generation is designed to host all the measurement setups and to receive all the beams of interest, produced either by SPIRAL1 with the highest intensities for the lightest ones or by S3-LEB for the heaviest and the most exotic ones. An intelligent sharing of the beams between several setups or even the use of different beams in parallel would allow the optimized achievement of the experiments which require long periods for tests, tuning and data taking. Such a situation is of course easier to be managed if the facility is in France, for which the French community has developed tailored setups. The consequent reduction of the Carbon impact could also be a crucial ecological argument for the future. To emphasize again, this program depends on the long-term availability of SPIRAL 1 beams, the most efficient source of light radioactive beams at GANIL.

[2] See contribution entitled : "DESIR at SPIRAL2/GANIL"