WISArD
Conseil Scientifique IN2P3

Maud Versteegen for the WISArD collaboration

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1. Executive Summary

Nuclear beta decay has played a crucial role over the past century in establishing key properties of the electroweak sector of the Standard Model (SM), such as the existence of the neutrino or parity violation. High precision measurements of nuclear beta decay observables still play a major role for particle physics research to this day. They are pivotal to determine numerical values of fundamental parameters of the SM, such as the Cabibbo-Kobayashi-Maskawa (CKM) matrix element V_{ud} [1]. They provide stringent tests of the existence of New Physics (NP), in the form of new particles which would alter corrected half-lives, decay distributions or correlation coefficients with respect to SM predictions [2]. When they reach the 0.1% level of precision, the constraints they set are at the same level as the ones set by direct searches for NP performed at high energy at LHC [3, 4].

The WISArD project is part of this effort and aims to improve the constraints on the existence of exotic Scalar currents in the weak interaction, by extracting both the angular correlation coefficient $a_{\beta\nu}$ and the Fierz interference term b in the nuclear beta decay of $^{32}\mathrm{Ar}$ at a precision level of 0.2-0.1%. This level of precision is a factor of 2 to 4 better than the best measurement to date of $a_{\beta\nu}$ in a pure Fermi decay, which is at 0.48% [5]. In allowed beta decays, both $a_{\beta\nu}$ and b can be accessed in the high-precision measurement of the angular distribution between the two leptons and of the beta spectrum shape. In a pure Fermi beta decay, both $a_{\beta\nu}$ and b can be expressed as functions of the standard Vector and the exotic Scalar effective coupling constants. Any deviation from the $a_{\beta\nu} = 1$ and $b = 0$ values predicted by the SM would sign the existence of Scalar couplings in the weak interaction. In pure Gamow-Teller decays, a deviation from $a_{\beta\nu} = -1/3$ and $b = 0$ can be looked for to test the existence of Tensor couplings.

The WISArD set-up is installed in the ISOLDE experimental hall, at CERN. It is composed of a 9T superconducting magnet, within which a detection set-up comprising 8 DSSDs[1], 1 beta detector, 1 MCP[2] and 1 Faraday cup is installed to perform a measurement of the angular distribution between the 2 leptons. The detection stage is versatile and can easily be modified, allowing us to also perform beta spectrum shape measurements. For this purpose, the high magnetic field is taken advantage of to obtain a 4π detection geometry for such measurements, to confine backscattered beta particles in the detection region.

The proof-of-principle experiment of WISArD took place in 2018 and already yielded the world's 3^{rd} best result on the modified $\tilde{a}_{\beta\nu}$ parameter, which contains both $a_{\beta\nu}$ and b dependencies, with a total uncertainty of $\sim$4% [7]. The complete detection set-up was upgraded during CERN LS2[3] (2019-2021), with dedicated high resolution DSSDs, a specific cooling system for the detectors and the electronics, a new beta detector and beam transport and monitoring instruments. New data taking in 2021 allowed us to test the new set-up and reached a 2% statistical uncertainty, systematic errors still being under analysis. The latest data taking took place in May 2024 and the statistics of 11×10^6 events needed to reach the 0.2% level of statistical uncertainty was achieved. Systematic uncertainties have to be precisely determined but we expect them to also be at this level. A first beta spectrum shape measurement was also carried out during CERN LS2 on $^{114}\mathrm{In}$, with original results on the weak magnetism parameter b_{WM} measured for the first time in the mass range of fission products [8].

The WISArD project is a collaboration of about 15 people from 2 French IN2P3 institutes,

[1] Double-sided Silicon Strip Detector
[2] Micro-Channel Plate
[3] Long Shutdown II

LPC[4] Caen and LP2i[5] Bordeaux, as well as collaborators from the KU Leuven, the Institute for Basic Science (IBS), Korea, the SCK·CEN Research Center, Mol, the Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering (IFIN-HH), Romania, and the Nuclear Physics Institute (UJF), Czech Republic. It obtained an ANR grant of 702k€ in 2018 which ends in 2024 and is supported by a FWO grant from Belgium of 405k€.

In the near future, the sensitivity of the WISArD set-up to $a_{\beta\nu}$ and b in the beta decay of ^{8}Li will be investigated to assess its competitiveness with recent results [9] in the hopes of taking data before CERN LS3 (2026-2028). New beta spectrum shape measurements are also being set-up in collaboration with KU Leuven, with several source measurements planned over the next three years and beam measurements foreseen after CERN LS3.

2. Scientific Motivation

The SM of particle physics is without a doubt one of the greatest achievements in fundamental physics, with a predictive power verified many times over, one of the last time being the confirmation of the existence of the Brout-Englert-Higgs boson in 2012 [10]. However, despite its spectacular success, open questions remain, such as the nature of dark matter, the origin of parity violation, the observation of neutrino oscillations, or the origin of matter-antimatter asymmetry. The search for NP to extend the SM and explain these observations has actively been going on over the past 50 years at the energy, intensity and precision frontiers. NP is looked for directly in the form of new particles at the energy frontier, in such experiments as ATLAS and CMS at LHC, and its existence is tested at the intensity and precision frontiers in the form of deviations from SM predictions, in experiments such as Belle II and many different low energy projects.

Beta decay plays a particular role in this context. It is a process occurring at energies of the order of the MeV in complex systems, e.g. nuclei and the neutron to a lesser extent, whereby an up u quark is transformed into a down d quark, or vice versa, by the exchange of a $W^{\pm}$ boson. It is governed by the weak interaction at the most fundamental level known today and can be used to test the existence of NP in this sector of the SM.

The most general form of the hamiltonian for neutron beta decay was established by Lee and Yang in 1956 [11] :

$$\mathcal{H}_\beta = g \sum_{i=S,V,T,A,P} \underbrace{\bar{p}\mathcal{O}_i n}_{\mathcal{H}_{\rm had}} \underbrace{\bar{e}\mathcal{O}_i(C_i + C_i'\gamma_5)\nu}_{\mathcal{H}_{\rm lep}} + h.c. \tag{1}$$

with $g = G_F V_{ud}/\sqrt{2}$ the overall strength of the interaction, G_F being the Fermi constant and V_{ud} the first top row element of the CKM matrix, and $\mathcal{O}_i$ being the Lorentz invariant operators of the interaction, expressed in terms of the γ matrices. Together with the interacting hadronic and leptonic fields, n, p and e, ν respectively, they form the hadronic and leptonic currents[6]. The effective coupling constants C_i render the relative amplitude of each interaction. In the most general form, requiring only Lorentz invariance, all Ci coefficients are complex, corresponding to a total of 20 parameters, one of them being fixed following the Conserved Vector-Current (CVC) hypothesis : $C_V \equiv 1$.

In the SM, the weak interaction is described in the framework of the "V-A" theory, involving

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[5] Laboratoire de Physique des 2 infinis

[6] S=Scalar, V=Vector, T=Tensor, A=Axial-Vector, P=Pseudoscalar

only the Vector and Axial-Vector interactions. Time reversal is conserved, meaning that all C_i's are real. Maximal parity violation is assumed, as was observed experimentally in nuclear beta decay [12], with only left-handed currents, which implies that both C_i and C_i' are non zero with $C_i = C_i'$. In terms of the effective coupling constants introduced in Eq. (1), the SM prescription translates as $C_V = C_V' = 1$, $C_A = C_A'$ and $C_S = C_S' = C_T = C_T' = C_P = C_P' = 0$. Part of the effort to search for NP in the weak sector is directed towards the existence of Scalar and Tensor currents[7], referred to as *exotic* with respect to the standard Vector and Axial-Vector currents.

Several beta decay parameters are directly linked to the effective coupling constants C_i and are used to test the existence of exotic currents, namely the correlation coefficients involved in the energy and angle distribution of the beta particle in allowed transitions and corrected $\mathcal{F}t$ values[8] in particular. High precision determinations of $\mathcal{F}t$ values for super-allowed $0^+ \to 0^+$ transitions and mirror decays over the past 3 decades have been carried out to that end [6, 13, 14], as well as high precision measurements of the beta-neutrino angular correlation coefficient $a_{\beta\nu}$, the Fierz interference term b and the beta asymmetry parameter A. The precision of these measurements is at the level of 0.5% or better. See Ref. [2] for a recent review of the existing results and planned experiments.

A renewed interest in the comparison between the constraints set on NP by ultra-high precision beta decay experiments and searches at ultra-high energy led to several seminal papers over the past 5 years presenting global analysis of the data in the framework of model-independent Effective Field Theories (EFT), see e.g. Ref. [2, 3, 14, 15]. In the prescription of EFTs, the impact of NP, such as hypothetical W' bosons or leptoquarks, is parametrised in the quark-level lagrangian of the weak interaction using wilson coefficients, denoted as ϵ_i and $\tilde{\epsilon}_i$ with $i = S, V, T, A, P$. These coefficients are defined with respect to the SM contribution and scale as [2] :

$$\epsilon_i, \tilde{\epsilon}_i \propto \left(\frac{m_W}{\Lambda_{NP}}\right)^n \tag{2}$$

where $n = 2$ in the simplest case, m_W is the mass of the $W^\pm$ bosons and Λ_{NP} is the NP energy scale. For $\epsilon_i, \tilde{\epsilon}_i \sim 10^{-3}$, the NP scale is at the TeV level. Using the EFT "ladder", the C_i coupling constants of the Lee-Yang nucleon-level effective theory can be expressed as linear combinations of the $\epsilon_i, \tilde{\epsilon}_i$, making beta decay measurements at the precision levels of 0.1% probe NP at the TeV scale, as is at the energy frontier.

Figure 1 shows the result of the latest global analysis using the EFT prescription [3]. The 90% CL constraints on Scalar and Tensor EFT Wilson coefficients ϵ_S and ϵ_T obtained from existing beta decay data and from high-energy physics data are shown to be at the same level on the existence of Scalar currents.

To stay competitive with the projected constraints from high-energy physics, high-precision beta decay experiments must further improve to go down to the 0.1% level of precision [2]. Pursuing this goal is essential to show that complementary approaches in very different energy domains are able to yield similar outcomes.

[7] Pseudoscalar currents are ruled out at the present level of precision by π leptonic decay [4]

[8] The ft value is the product of the partial half-life of the beta transition t and the integrated phase space f

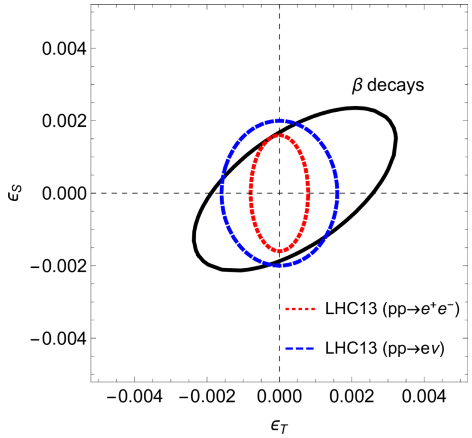


Figure 1: 90% CL constraints on Scalar and Tensor EFT Wilson coefficients obtained from beta decays and from LHC data, extracted from Ref. [3].

3. The WISArD project

In the WISArD project, we aim to extract the angular correlation coefficient $a_{\beta\nu}$ and the Fierz interference term b from the super-allowed pure Fermi beta decay of $^{32}\mathrm{Ar}$ with a relative precision of 0.2-0.1%. Pure Gamow-Teller decays are also accessible in the data, but this level of precision is most likely not achievable.

Angular correlation measurement

The distribution in electron energy and angle and in neutrino angle of allowed beta decays for unpolarised nuclei was derived from the Lee-Yang hamiltonian, neglecting recoil-order and electromagnetic corrections, by Jackson, Treiman and Wyld in 1957 [17]:

$$\mathcal{W}(E_e,\Omega_e,\Omega_\nu)\,dE_e d\Omega_e d\Omega_\nu = \frac{F(\pm Z,E_e)}{(2\pi)^5} p_e E_e (E_0-E_e)^2 dE_e d\Omega_e d\Omega_\nu \times \xi \left[1 + a_{\beta\nu}\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_e E_\nu} + b\,\frac{m_e}{E_e}\right] \tag{3}$$

It involves the total energy E_e, momentum $\vec{p}_e$ and angle Ω_e of the beta particle, the maximum total energy E_0 of the beta particle and m_e, the electron rest mass. Similar notations are used for the neutrino. $F(\pm Z, E_e)$ is the Fermi function, with Z the atomic number of the daughter nucleus and $\pm$ refers to $\beta^{\mp}$. The ξ coefficient is a quadratic combination of C_V, C_S, C_A and C_T and of the Fermi (F) and Gamow-Teller (GT) nuclear matrix elements M_F and M_{GT}.

Pure allowed F decays correspond to $\Delta J = 0$ between initial and final states and anti-aligned lepton spins. They are driven by the Vector current of the weak interaction. Pure allowed GT decays correspond to $\Delta J = 0$ and aligned lepton spins, and are driven by the Axial-Vector current. The predicted numerical value of $a_{\beta\nu}$ by the strict "V-A" structure of the weak interaction is $a_{\beta\nu} = 1$ for a pure F decay and $a_{\beta\nu} = -1/3$ for pure GT decays. The values of the Fierz interference term in both transitions are $b = 0$. Any admixtures of Scalar currents in F decays or Tensor currents in GT decays would result in a measurable deviation from the SM expectated value such that :

$$
\begin{aligned}
a_{\beta\nu}^{F} &\simeq 1-\frac{|C_S|^2+|C'_S|^2}{|C_V|^2} & b^{F} &\simeq \pm\mathrm{Re}\left(\frac{C_S+C'_S}{C_V}\right) \\
a_{\beta\nu}^{GT} &\simeq -\frac{1}{3}\left[1-\frac{|C_T|^2+|C'_T|^2}{|C_A|^2}\right] & b^{GT} &\simeq \pm\mathrm{Re}\left(\frac{C_T+C'_T}{C_A}\right)
\end{aligned} \tag{4}
$$

The angular correlation coefficient $a_{\beta\nu}$ governs the angular distribution between the beta and the neutrino. Rather than detecting the motion of the neutrino itself, it is determined from the nuclear recoil distribution. The SM value favours small angles in pure F decays, corresponding to preferred large nuclear recoils. On the contrary, large angles and small nuclear recoil are favoured in pure GT decays. Such recoil measurements can not disentangle the contributions of $a_{\beta\nu}$ and b, they extract the corrected $\tilde{a}$ parameter [18] :

$$
\tilde{a}_{\beta\nu} \simeq \frac{a_{\beta\nu}}{1+\alpha b} \tag{5}
$$

where α denotes the sensitivity to b, which depends on both the set-up geometry and the mean value $< m_e/E_e >$ over the beta energy spectrum (see Ref. [18] for more details).

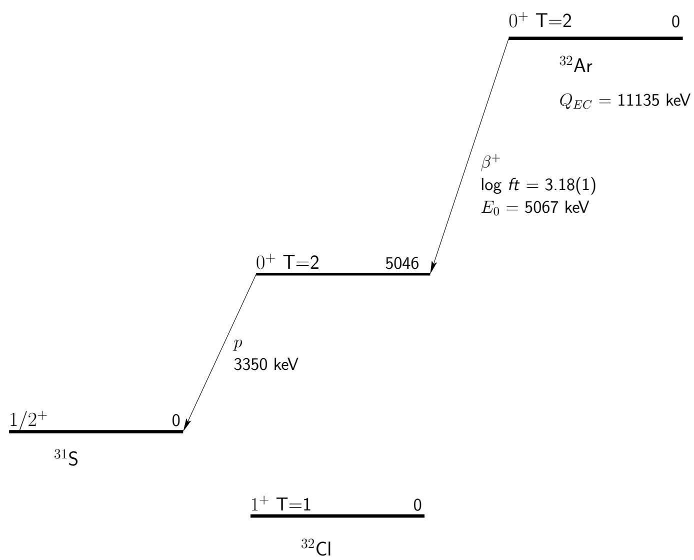
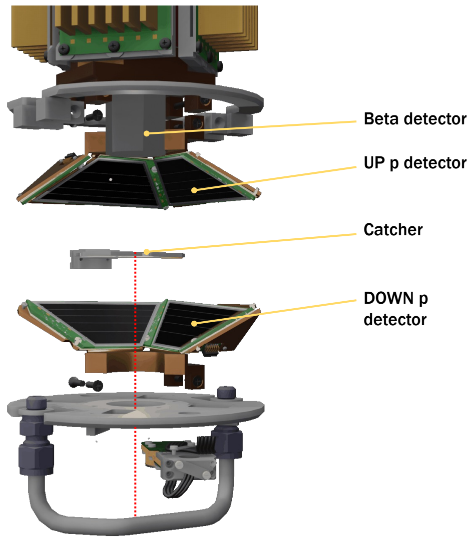
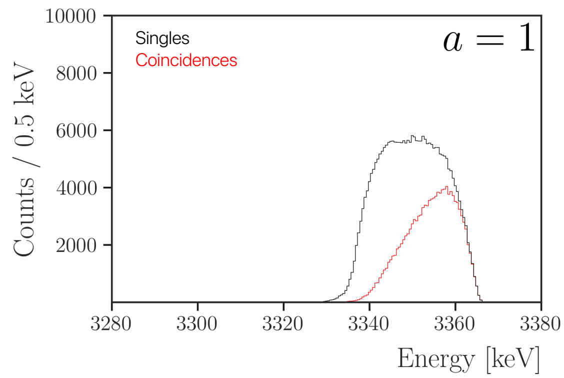


Figure 2: Part of the decay radiation scheme of the super-allowed $0^+ \to 0^+$ beta decay of $^{32}\mathrm{Ar}$ (branching ratio 23%) to the IAS in $^{32}\mathrm{Cl}$ which then decays to the $^{31}\mathrm{S}$ ground state via the emission of a 3353 keV proton.

Nuclear recoil energies following allowed beta decay are of the order of a few tens of eV to a few keV, which makes their measurement to a high level of precision particularly challenging [19, 20]. In exotic nuclei where beta-delayed particle emission occurs, it has been shown that the nuclear recoil, hence the angular correlation coefficient, can be accessed from the energy distribution of the delayed particle emitted in flight from the recoiling daughter nucleus [21]. The advantage of beta-delayed particle experiments is that the unstable states populated in the daughter nucleus are so short-lived that the daughter nucleus does not interact with neighbouring atoms before the



(a) CAD drawing of the WISArD 2024 experimental set-up, placed in a 9T superconducting magnet.



(b) GEANT4 Monte Carlo simulation of beta-delayed protons from ^{32}Ar detected in the DOWN p detector, in the SM prescription. (Credit S. Lecanuet).

Figure 3

delayed emission. The energy of the beta-delayed particle is also of the order of a few MeV, which is significantly easier to detect with conventional techniques and less sensitive to scattering and energy loss in the source medium.

One of the best measurement to date of $\tilde{a}_{\beta\nu}$ for a pure F transition was obtained in the early 2000's using the beta-delayed proton emission of ^{32}Ar [16]. It yielded a relative uncertainty of 0.65%. Figure 2 shows part of the beta-delayed proton decay of ^{32}Ar. The ^{32}Ar ground state decays to its isobaric analogue state (IAS) in ^{32}Cl via the super-allowed $0^+ \to 0^+$ β^+ transition (branching ratio ∼22.7%). The IAS decays via proton emission to the ^{31}S ground state. As the IAS has a width of $\Gamma = 20(5)$ eV [22], corresponding to a lifetime of 0.033(8) fs, the ^{32}Cl daughter travels at most about 0.02 Å before emitting the proton. The recoiling ^{32}Cl therefore emits the proton while still travelling at full velocity from the lepton recoil, without any hampering by atoms of the catcher foil the ^{32}Ar are collected in. The proton energy distribution in the laboratory frame reflects the full kinematics of the preceding beta decay. The corresponding broadening of the proton energy distribution was first measured in 1993 [23] with cooled silicon detectors and then improved in 1999 using 2 cooled *p-i-n* diodes with ∼3 keV pulser resolution [16]. In both experiments the β^+ particles were not detected, although the detection set-up was placed in a high magnetic field to guide them out of the sensitive area in the latter.

In the present project, we measure β-p coincidences in the decay of ^{32}Ar and extract the kinematic *shift* between single IAS proton events and IAS protons in coincidence with a β^+ emitted in the same or the opposite direction to the proton. Such a differential measurement is less sensitive to the effects of noise and detector response function, which makes it easier to reach higher precision. Events where the protons are emitted in the same or the opposite hemisphere as the β^+ particle are also the ones most sensitive to the kinematic effect due to the recoil, which enhances our sensitivity.

Figure 3a shows the WISArD 2024 experimental set-up. It is composed of 1 beta detector, made

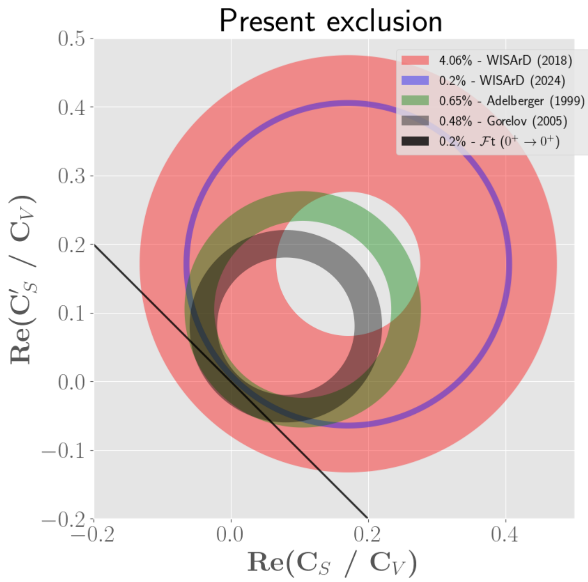


Figure 4: Constraints on exotic Scalar currents set by ultra-high precision beta decay measurements. (Credit D. Atanasov)

of a cylindrical plastic scintillator 3 cm in diameter coupled to an array of 9 SiPMs[9], and 2 proton detectors, each made of 4 DSSDs covering a total solid angle of about 50%. The p detectors are placed symmetrically with respect to a catcher foil where the $^{32}\mathrm{Ar}$ beam is implanted. The whole set-up is placed in a 9T superconducting magnet, which is set at 4T during data taking. This value ensures ∼100% total detection efficiency of all β^+ particles emitted in the upper hemisphere, the most energetic of them having a radius of curvature of ∼8 mm. All detectors and associated electronics are cooled down to about -17°C, by both an active glycol cooling system and the magnet bore. Figure 3b shows GEANT4 Monte Carlo simulations of IAS protons detected in the DOWN detector, with and without a β^+ in coincidence in the beta detector (event generator : CRADLE++[26]). These simulations take into account the dead layer of the detectors, their resolution and the catcher thickness. The kinematic broadening of the total singles spectrum is clearly visible as well as the boost in energy of the protons emitted in the same direction as the nuclear recoil. The kinematic shift between the two spectra depends on the DSSD strip and is close to ∼4.5 keV in the ones closest to the beam axis.

The first advantage of the WISArD experiment is the measurement of high energy particles, namely protons of 3.5 MeV, in comparison to direct measurements of nuclear recoil, which do not exceed a few keV and are thus strongly affected by the source characteristics (ion cloud size, temperature, varying background etc.). The second advantage is the already mentioned differential measurement type, between events in identical detectors, which significantly reduces the impact of noise and of the p detector response functions on the final systematic uncertainty. Measuring the full β^+ energy spectrum allows us to perform checks of systematic effects which would vary with the β particle energy. The constraints on the beta detector are however not drastic, as its main purpose is to tag β^+ particles emitted in one hemisphere. It does not need a particularly high resolution. Several pure GT transitions from $^{32}\mathrm{Ar}$ are also subject to beta-delayed proton emission (see e.g. Ref. [24] for a detailed study of $^{32}\mathrm{Ar}$ decay) which allows us to follow very

[9]Silicon PhotoMultiplier

closely gain drifts of the p detectors. Calibration can then be done with dedicated ^{33}Ar data at regular intervals during data taking [27]. The added bonus is that the GT delayed-proton groups also allow us to perform the same study for GT beta decay and extract constraints on the contribution of Tensor currents to the weak interaction. The expected sensitivity through the Fierz term b (see Eq. (5)) is however expected to be low [7].

Figure 4 shows the allowed region in the C'_S vs C_S plane, set by $\mathcal{F}t$ values [13] and the best measurements of $\tilde{a}_{\beta\nu}$ to date [5, 16] as well as the expected constraint from the WISArD result at 0.2% relative precision. The improvement with respect to previous experiments can clearly be seen.

β Spectrum Shape Measurement

The sensitivity to NP in beta decay experiments primarily comes from the Fierz interference term b, which has a linear sensitivity to Scalar and Tensor currents (see Eq. (4)). Angular correlation measurements are sensitive to b through $\tilde{a}_{\beta\nu}$. Beta spectrum shape measurements directly probe b as the Fierz term is the only surviving term in the decay rate distribution, in absence of nuclear polarisation and without a measurement of the direction of the neutrino nor of the nuclear recoil (see Eq. (3)). The impact of beta spectrum shape measurements recently attracted renewed interest as a complementary, sensitive probe to potential NP [28]. In order to reach conclusions on NP, the beta spectrum shape needs to be described at the ‰ level of uncertainty, which has been the focus of recent revisited theoretical work [29], and SM corrections which were neglected due to insufficient experimental precision need now to be carefully evaluated and checked. One such effect is induced by the strong interaction on the weak interaction process, as the quark involved in the beta decay is bound in a nucleon, and not free. This effect is dominated by the weak magnetism form factor [29]. Ref. [6] provides an overview of current experimental and theoretical knowledge of weak magnetism, which is the most important recoil-order correction to the beta spectrum shape. The interest in performing high-precision beta spectrum shape measurements is thus twofolds : first, it allows us to test and constrain known SM effects, such as weak magnetism, and secondly, it is a sensitive probe to NP in the form of exotic Scalar and Tensor currents.

High-precision beta spectrum shape measurements are particularly challenging, as electrons are subject to partial energy deposit in charged particle detectors, due to backscattering, out-scattering and Bremsstrahlung, as well as to energy loss in the source itself and in the detector dead layer. To overcome these difficulties, different 4π detection techniques have been developed. The bSTILED project uses 2 Phoswich PVT-YAP detectors in a closed geometry [30] and the MiniBETA project uses a multiwire chamber for instance [31].

In the WISArD project, the detection system used for the angular correlation measurement can be swapped for a dedicated beta spectrum shape measurement set-up. The constraint of needing a closed detection system to cover a 4π solid angle is lifted by the magnetic field. Backscattered events from one detector can be directed by the magnetic field to a symmetrical counterpart, and the energies summed, provided careful gain calibration is performed.

A first test of such a measurement was performed at WISArD with ^{114}In in 2020. Two beta detectors, composed of a cylindrical plastic scintillator 2 cm in diameter coupled to 1 Hamamatsu SiPM with temperature gain regulation, were placed symmetrically with respect to the source, inside the bore of the superconducting magnet. Calibration measurements were performed with ^{207}Bi and ^{137}Cs sources, as well as beta spectrum shapes with ^{114}In and ^{90}Sr/^{90}Y sources, at different magnetic fields up to 6T. The analysis of the data shows promising results, with a new measured value of the weak magnetism form factor in the mass region of fission fragments [8]. This first measurement is, however, limited by the detector characterization, which is hampered by the large resolution of the detectors, as well as the non-linearity of the SiPM and the high sensitivity of their gain to temperature changes and drifts.

New measurements are foreseen, with a new detection set-up based on Si(Li) detectors [32]. The backscattering probability of silicon, higher than the one of the light elements composing the plastic scintillator, is expected to be mitigated by the much higher resolution and lower detection threshold.

4. Timeline

The WISArD project started in 2016, when the recommissioning of the WITCH magnet and beam line [20] at ISOLDE, CERN, started. In the following we will present the major steps of the project.

2018 : Proof-of-principle Experiment

A first data taking in $^{32}\mathrm{Ar}$ was performed in November 2018, with readily available detectors within the collaboration. Eight 300 μm thick silicon detectors 20 mm in diameter were placed on two symmetrical planes for proton detection and a plastic scintillator 2 cm in diameter coupled to one SiPM was used for positron detection. Figure 5 shows a schematics of the WISArD horizontal and vertical beam lines (HBL and VBL) leading to the superconducting magnet bore, where the detection set-up was installed. It is inserted from the top flange to reach the 9T region 3m down. A picture of the WISArD platform at ISOLDE is also shown.

Only 3 days (36h) of data taking with about half the nominal production yield of $^{32}\mathrm{Ar}$ were taken. The experiment was still a success as it allowed us to identify all main sources of systematic uncertainties and yielded the world's 3$^{\mathrm{rd}}$ best result on $a_{\beta\nu}$, with a ∼4% relative uncertainty [7]. No showstopper was identified and all systematic effects were expected to be manageable to the ‰ level of precision with state-of-the-art detectors. The main sources of systematic uncertainty are the p detectors calibration, which is improved with new detectors the dead layer of which are thinner and precisely characterised offline, the source position, which is imaged with a new dedicated MCP detector, the β^+ backscattering in the catcher and in the beta detector. To reduce these effects, different catcher thicknesses are used, the beta detector threshold will be lowered and careful studies of the GEANT4 backscattering models will be performed.

The WISArD project obtained a first grant of 405k€ from FWO by our collaborators from KU Leuven. The ANR project was also approved in 2018, for a total amount of 702k€. It allowed us to upgrade the whole detection set-up and hire a PhD student and a Post-Doctoral fellow.

2019-2021 : CERN LS2

During CERN LS2 the WISArD set-up was fully upgraded, with a new detection tower, new state-of-the-art silicon detectors with high resolution and small dead layer, a new beta detector and several new instruments to monitor and transport the beam through the beam line with maximum efficiency [33]. All vacuum systems along the beam line were also renewed and a new EPICS control system was developed.

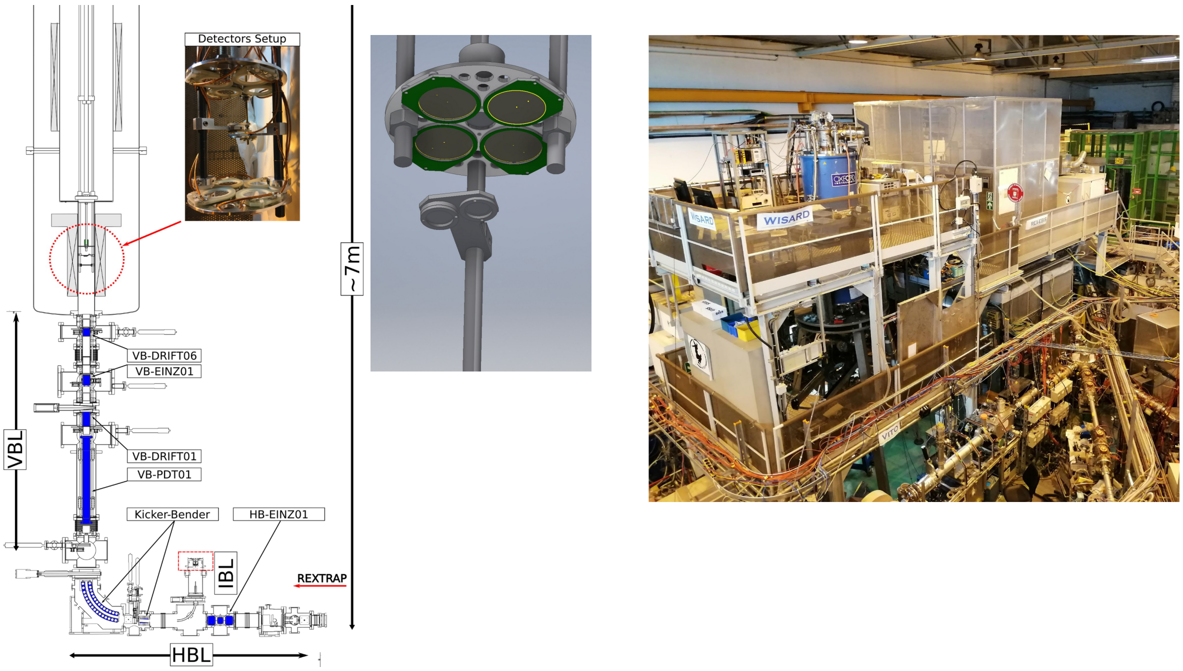


Figure 5: Schematics of the WISArD beam lines and of the proof-of-principle detection set-up, picture of the WISArD platform at ISOLDE.

In 2020, during COVID, we performed the first β spectrum shape measurement at WISArD, using a ^{114}In source. A dedicated set-up was mounted, with closed geometry. Two plastic scintillators each coupled to one SiPM with temperature regulated gain were installed symmetrically with respect to the source inside the superconducting magnet. Calibration runs at different magnetic fields were measured to constrain systematics. The analysis of this data was the work of S. Vanlangendonck's PhD, to extract the weak magnetism recoil-order correction [8]. The result is in agreement with recent results from MiniBETA [31], but further work is needed and is ongoing to fully understand systematic effects.

2021: First ^{32}Ar Data Taking

After the successful proof-of-principle experiment of 2018, we performed a test experiment to validate the most crucial upgrades of the apparatus in October 2021. The beam-transport efficiency to our setup improved from about 15% in 2018 to close to 90% in 2021. The new silicon detectors had been tested with a 700 keV alpha beam at the AIFIRA accelerator of LP2iB in 2020. The energy resolution achieved was 10 keV (FWHM) compared to about 35 keV for the 2018 experiment, improving the sensitivity of the experiment by a factor of $\sim$2, and the dead layer was measured to be $\sim$100 nm. The new geometry of the proton detection stage now covers a solid angle of about 50% improving the angular coverage by a factor of 7. Finally, the new positron detection system consists now of a 3 cm in diameter and 5 cm long plastic scintillator coupled to a matrix of nine silicon photomultipliers, to reduce the detection threshold.

We took 10 shifts of data, with two different catcher foil thicknesses. However, only half of the detectors performed with nominal resolution due to a lack of testing time. Even so, the accumulated statistics was still improved with respect to 2018 by a factor of 2.

2021-2023: Tests and Improvements

Improvements of the detection set-up were implemented after the 2021 test run. The mechanical support of the p detectors was remade, to improve cooling efficiency and ease the mounting of the 8 DSSDs. A 3-stage MCP was developed and tested to image the beam and precisely know its size. We managed to have it successfully work in the magnetic field up to 4T. New catcher holders were made, to have 2 catcher thicknesses and 1 calibration alpha source at the same time in the set-up. Two measurement campaigns were performed at the AIFIRA accelerator of LP2I in March and July 2022 to precisely map the dead layer thickness and measure the resolution of all the DSSDs with 700keV α and monoenergetic p data. Dedicated measurements were also performed with monoenergetic electrons and a ^{207}Bi source to understand the response function of the SiPM of the beta detector.

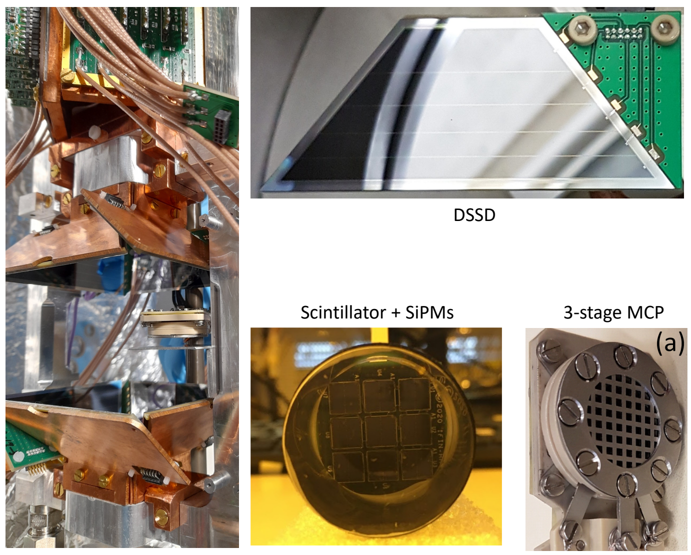


Figure 6: Pictures of the WISArD detection set-up with close-ups on 1 DSSD, the β detector and the triple-stage MCP.

Figure 6 shows the main parts of the detection system. The MCP is placed at the bottom of the detection set-up and not at the position of the catcher, due to space limitation.

2024: second $^{32}\mathrm{Ar}$ Data Taking

The second $^{32}\mathrm{Ar}$ data taking was performed early May 2024 and was a complete success. All 48 strips of the p detectors worked at nominal resolution during the 10 days of beam time. The transmission efficiency through the beam line was above 80% and the production rate of $^{32}\mathrm{Ar}$ went up to 2000 pps/μA during 2.5 days. Unfortunately the ISOLDE target line broke before the end of the experiment but we still managed to accumulate 11×10^6 IAS singles proton events, which is the necessary statistics to reach 0.2% of relative statistical uncertainty.

Figure 7 shows a typical p spectrum measured in strip 1, which is closest to the beam axis. The distribution of events with and without a β particle in coincidence in the beta detector is shown in the inset. All known p groups have been identified [24], as well as α peaks due to α

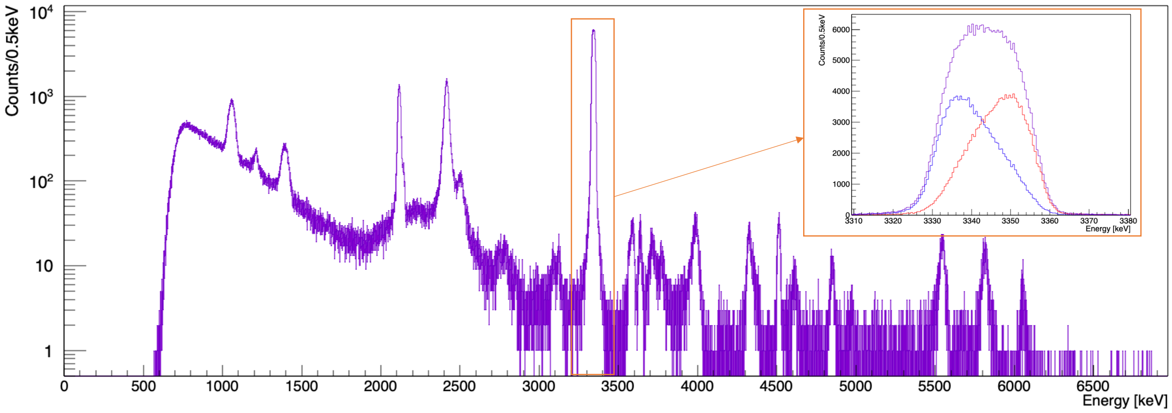


Figure 7: Total p spectrum in 1 strip closest to the beam axis of one DOWN detector. (violet : singles p events; red : β-p coincidence events; blue : p events without β in coincidence)

decay of ^{18}N^{14}N molecules. Please note that this is preliminary online data which explains why the IAS peak is not at 3353 keV as the calibration needs to be refined on each strip. Nevertheless, the kinematic broadening of the IAS peak is however clearly visible.

Short Term Prospects (3-5 years)

The latest data taking with ^{32}Ar from May 7 to 17 2024 will be carefully analysed within the next 2 years. A precise account of the systematic uncertainty will be performed. Finalizing the analysis of the 2021 run and the complete analysis of the 2024 data is the PhD work of S. Lecanuet.

New data taking is foreseen in 2025, before CERN LS3 (2026-2028), either on ^{32}Ar or on ^{8}Li. Preliminary analysis of the systematics of the 2024 ^{32}Ar data will tell us if we can reach the 0.1% of relative systematic uncertainty and if getting more statistics is worth it. Otherwise, the triple coincidence in the beta-delayed 2-α break-up of ^{8}Li can be measured with the WISArD set-up but the sensitivity of its geometry to $a_{\beta\nu}^{GT}$ and b^{GT} must be assessed to ensure its competitiveness with latest results [25]. Monte Carlo simulations are foreseen in the next months.

New β spectrum shape measurements are also planned within the next 3 years. The set-up used in the ^{114}In measurement is being upgraded with new Si(Li) detectors and the associated cooling system, to improve drastically both the resolution and the detection threshold. The project will start with characterisation measurements with and without magnetic field to evaluate the effect of backscattering on the new detectors, and will be followed by several source measurements during CERN LS3. It will cover 2 PhD thesis, one in KU Leuven and one at LP2i Bordeaux. The ^{114}In measurement will be reproduced, and new data with ^{32}P or ^{22}Na are foreseen. Allowed transitions with a high logft-value, such as ^{32}P with logft = 7.2, are a useful probe for nuclear structure effects in the study of recoil-order SM corrections, weak magnetism in particular, because their relative importance is enhanced. ^{22}Na is a source measurement which will serve as a proof-of-principle experiment for the foreseen high-precision beta spectrum shape measurement of ^{14}O, which is discussed below.

Long Term Prospects

High-precision beta shape measurement of ^{14}O are planned after CERN LS3 to improve the uncertainty on the branching ratio of the $0^+ \rightarrow 0^+$ superallowed transition by a factor 2 to 3. A measurement at the % level of relative uncertainty of the beta spectrum shape should allow us to reach the ‰ level of uncertainty on the BR, which is currently 99.446(13)%. We plan on measuring the BR of the ground-state-to-ground-state decay which is currently fixed at 0.500(13)% with a precision of 1%. Such a measurement requires a new detection set-up, similar to the ones foreseen for the source beta shape measurements but with a moving down detector to allow the radioactive beam to go through. This effort is necessary to lower the contribution of the BR uncertainty to the total error budget of the $\mathcal{F}t$ value of ^{14}O, which is one of the two superallowed $0^+ \rightarrow 0^+$ decay, with ^{10}C, which has the greatest weight in the most stringent limit on Scalar currents to this day [13].

In the long term future, the WISArD set-up will most probably be duplicated at DESIR, GANIL, to perform new beta spectrum shape and angular correlation measurements, such as with ^{20}Mg. The kinematic shift in ^{20}Mg is 15% higher than for ^{32}Ar and the sensitivity to Scalar currents is thus expected to be improved. However, high production rates are needed, as the absolute p intensity of the IAS is about 1%.

5. Environment and IN2P3 Contribution

Similar projects, but with a longer timescale, are being prepared. At Texas A&M University, a Penning trap will be used to prepare the ^{32}Ar source [34]. A new measurement with ^{38m}K, also aiming at 0.1% total precision, is planned at TRIUMF [35]. As all experiments will use very different techniques leading to different systematic errors, they will serve as a cross-checks for one another.

In the WISArD collaboration, IN2P3 members play a major role :

- B. Blank (LP2i Bordeaux) is the co-spokesperson, with N. Severijns of KU Leuven. He is also the main coordinator of the detection system.
- P. Alfaurt (LP2i Bordeaux) is the technical coordinator for mechanics, command control and vacuum.
- S. Lecanuet (LP2i Bordeaux) is the PhD student in charge of the 2024 data analysis. His PhD funding comes from IN2P3.
- X. Fléchard (LPC Caen) is the main coordinator for the electronics, DAQ and MCP developments and tests.
- F. Cresto (LPC Caen) was the former PhD who worked on the 2021 data, funded by the ANR.

The collaboration between LP2iB and KU Leuven is also tight for the foreseen β spectrum shape measurements, with 2 PhDs starting on the project only 1 year apart in both teams.

6. Human Resources

A summary of FTE dedicated to the WISArD project is available below[10]. Permanent physicists and engineers from IN2P3 working, or having worked, for the project are :

- LP2i Bordeaux : P. Alfaurt, P. Ascher, B. Blank, L. Daudin, M. Gerbaux, J. Giovinazzo, S. Grévy, M. Roche and M. Versteegen
- LPC Caen : X. Fléchard, L. Leterrier, E. Liénard, D. Etasse

Ressources humaines ANR

	Partenaire	Chercheurs	ITA	temporaire	Total
2019 :	CENBG	0,6 ETP	2,0 ETP	0,3 ETP	2,9 ETP
	LPC Caen	0,5 ETP	0,2 ETP	0.15 ETP	0,85
2020 :	CENBG	1,0 ETP	1,0 ETP	2,0 ETP	4,0 ETP
	LPC Caen	0,4 ETP	0,3 ETP	1,0 ETP	1,7 ETP
2021 :	CENBG	1,0 ETP	0,5 ETP	1,0 ETP	2,5 ETP
	LPC Caen	0,4 ETP	0,6 ETP	1,0 ETP	2,0 ETP
2022 :	CENBG	0,8 ETP	0,4 ETP	0,5 ETP	1,7 ETP
	LPC Caen	0,3 ETP	0,2 ETP	1,0 ETP	1,5 ETP
2023 :	CENBG	0,8 ETP	0,2 ETP	0,2 ETP	1,2 ETP
	LPC Caen	0,3 ETP	0,1 ETP	0,05 ETP	0,45 ETP

7. Conclusion

All main technical challenges of the WISArD project have been tackled over the 2019-2023 period and are described in details in Ref. [33]. We conclude this document with a SWOT analysis of the project.

S The detection set-up for angular correlation measurement is tested and validated. Improvements can still be made, on the beta detector threshold for instance, but the collaboration possesses the know-how. Analysis tools and procedures have been developed on the 2018 and 2021 data, and will now be applied to the 2024 dataset using the REX of these previous works.

[10] CENBG is the previous name of LP2iB

W The analysis of the data to extract NP constraints strongly relies on Monte Carlo simulations. Backscattering is a well-known challenge for Monte Carlo simulations to reproduce, meaning that the beta detection threshold is a particular key ingredient. It must be as low as possible to rely as little as possible on the simulations to reproduce the missing coincidences. A compromise must be found with the DAQ dead time when triggering close to the detector intrinsic noise level.

O The kinematic shift measurement using $^{32}\mathrm{Ar}$ proposed in the WISArD project can also be performed with other beta-delayed proton emitters with a superallowed $0^+ \to 0^+$ transition, such as $^{20}\mathrm{Mg}$. The set-up, originally designed for $^{32}\mathrm{Ar}$ measurements, is also versatile and can be modified to perform beta spectrum shape measurement, which are also of great impact for NP searches in the weak sector.

T The WISArD set-up is permanently installed in the ISOLDE hall at CERN. Its development and maintenance requires regular stays at CERN, crucial to the testing and validation of the detectors onsite. The cost of these stays for the French collaborators was covered by the ANR funding up to now. A new project funding application has been submitted to the ANR, but without success yet. With no new project funding, the French part of the collaboration will need the IN2P3 support to maintain its activity in the project at the same level.

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