EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Addendum to Proposal IS678
for the ISOLDE and Neutron Time-of-Flight Committee

Weak interaction studies via beta-delayed proton emission

October 02, 2024

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Abstract:
We propose to perform simultaneous measurements of the β-ν angular correlation coefficient ($a_{\beta\nu}$) and the Fierz interference term (b) for pure Fermi and pure Gamow-Teller transitions from ^{32}Ar using the kinematic shift technique. The present addendum follows the successful proof-of-principle experiment in 2018, a test performed in October 2021, and a full-scale experiment in May 2024.

The 2018 experiment allowed us to investigate statistical and systematic effects influencing the level of precision of the technique. We demonstrated its applicability by obtaining the third most precise value of $a^F{}_{\beta\nu} = 1.007(32)_{\text{stat}}(25)_{\text{sys}}$ for the pure Fermi transition with only 1.5 days of beam time.

The 2021 run with about 10 shifts allowed testing the newly designed mechanical setup, the new silicon and plastic-scintillator+SiPM detectors and the partly new data acquisition and control system. This test demonstrated that the setup was operational.

In May 2024, we performed an 8-day experiment with a completely functioning experimental setup. Unfortunately, high outgasing rates with the two target-ion-source ensembles allowed us to have only about 3 days of good production rates. The present addendum requests again 8 days of beam time with a high-intensity ^{32}Ar beam. If the systematic uncertainties would unexpectedly turn out to be too high to justify a new data taking with ^{32}Ar, we would use about 9 shifts for a test with ^{8}Li at WISArD.

Requested shifts: 24

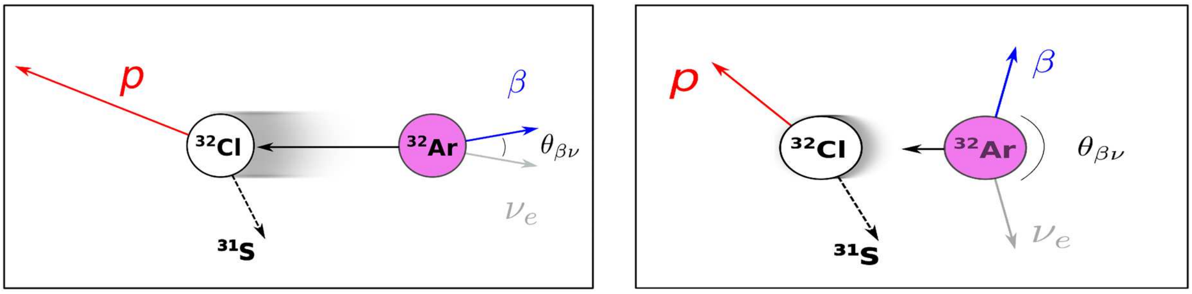
1. Motivation

Precision beta decay experiments are ideal tools to study the existence of physics beyond the standard model (SM) in the sector of weak interaction in a way that is complementary to high-energy experiments, e.g. at LHC. The minimal description of beta decay contains only vector (V) and axial-vector (A) currents. But the full form of the beta-decay Hamiltonian allows other Lorentz invariant current contributions, such as scalar (S) and tensor (T). The present experimental limits on the relative contribution of these interactions (i.e. scaler to vector, and tensor to axial vector) are derived mainly from correlation measurements, with the best current precision coming from the beta-neutrino correlation, $a_{\beta\nu}$, i.e. 0.65% for a pure Fermi transition (scalar interaction) and 0.7% for a pure Gamow-Teller transition (tensor interaction) [1, 2]. This level of precision still allows for a sizable contribution of these exotic currents without affecting the phenomenological conclusions for the weak interaction.

The SM value of the beta-neutrino angular correlation coefficient ($a_{\beta\nu}$) for the V-A structure of the weak interaction is $a_{\beta\nu} = 1$ for pure Fermi decays and $a_{\beta\nu} = -1/3$ for pure Gamow-Teller decays. The SM values of the Fierz interference term in both transitions is $b = 0$. Any admixtures of S or T currents to the dominant V and A currents would result in a measurable deviation from the SM value for b and/or $a_{\beta\nu}$.

2. Experimental technique and measurements

If the beta-decay daughter nucleus is unstable and subject to β-delayed particle emission, the momentum of the daughter nucleus can be determined by the kinematics of the decay products [3]. When a light energetic particle is emitted from a moving source (i.e. the recoiling daughter nucleus), its energy will be subject to a kinematic shift that reflects the motion of the moving source. Thus, one can study the energy spectrum of subsequently emitted beta-delayed particles, instead of the slow heavy nuclei. One such example is the decay of ^{32}Ar, where in Fig.1 a schematic representation of the V- and S-type kinematics is shown for the Fermi beta decay. Applying the kinematic shift technique in the case of ^{32}Ar requires the detection of coincidences between (i) the beta-delayed proton emitted by the recoiling ^{32}Cl daughter nucleus and (ii) the preceding positron. One then expects in case of a pure vector interaction a large energy shift for the proton (to lower or higher values depending on whether it is emitted parallel or antiparallel with the positron (Fig. 1 left panel) respectively, and almost no shift in energy for a scalar interaction (Fig. 1 right panel).



(a) Vector interaction (b) Scalar interaction

Figure 1: Schematic representation of the decay kinematics of a pure Fermi transition and its influence on the beta-delayed proton energy. The maximum emission probability occurs at $\theta_{\beta\nu} \sim 0°$ corresponding to the dominant vector interaction (a), while for a scalar contribution (b) the maximum occurs at $\theta_{\beta\nu} \sim 180°$.

An outcome of the coincidence requirement is the ability to study the energy shift of the entire proton spectrum observed, rather than focusing on a single transition, thus, allowing the simultaneous determination of the correlation coefficient in pure Fermi and pure Gamow-Teller transitions. One important advantage of this technique when compared to the best previous measurements based on broadening effects [4] comes from the less crucial knowledge of the properties of the charged-particle detectors: the proton energy shift between proton-positron coincidence events and singles proton events are independent, at first order, from the detector response function.

After the successful proof-of-principle experiment of 2018 [5], we performed a test experiment in October 2021 to validate the most crucial upgrades to the apparatus [6] as compared to the proof-of-principle experiment in 2018:

- The beam-transport efficiency from REXTRAP to our setup improved from about 15% in 2018 to close to 90% in 2021.
- The new silicon detectors have been tested with a 700 keV alpha beam of at the AIFIRA accelerator of LP2i Bordeaux. The energy resolution achieved was 10 keV (FWHM) compared to about 35 keV for the 2018 experiment. The new proton detection covers a solid angle of about 40% improving the angular coverage by a factor of 5 compared to the 2018 experiment.
- 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 (SiPM, 6x6mm^2 each). Each signal of the SiPM pixel is fed in a low-gain and a high-gain preamplifier to cover, on the one hand, the full beta-energy spectrum up to 10 MeV and, on the other hand, to lower the detection threshold to less than 10 keV.
- An MCP detector at the entrance of the setup allowed the fine-tuning of the beam in our setup to guarantee the correct positioning and focussing of the beam.

With this test successfully completed, a new full-scale experiment took place in May 2024. The complete experimental setup was working over the entire beam time with its expected performances. Only the MCP broke down at the end of the beam tuning. However, as the full setup including beam transport was extremely stable, this turned out not to be problem.
Figure 2 shows one spectrum from an upper strip (left) and one from a lower strip with the insets showing a zoom on protons from the isobaric analogue state (IAS), the highest peak in the spectrum.

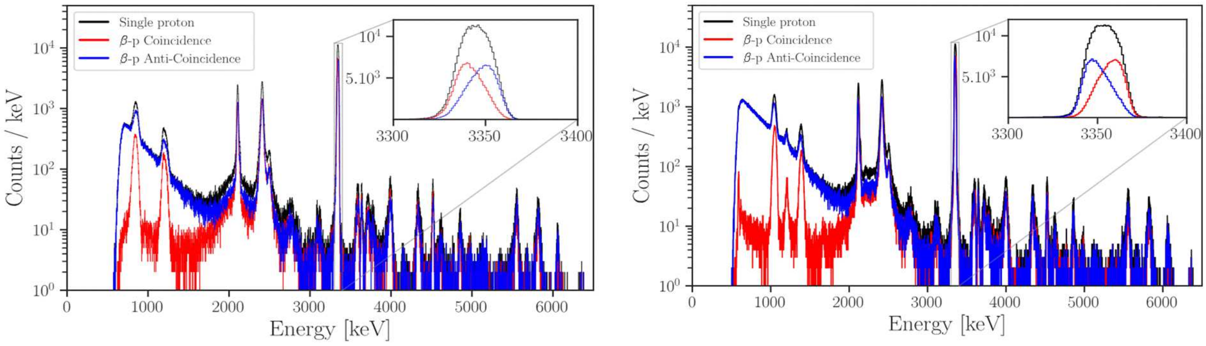


Figure 2: ^{32}Ar decay proton spectrum as acquired during the 2024 run for one silicon strip (out of 20) for the upper hemisphere (left) and one strip (again out of 20) for the lower hemisphere (right). The insets show the IAS proton peak (3353 keV) in singles mode as well as with and without beta coincidence.

statistical precision for the coefficient $a_{\beta\nu}$ for the Fermi decay to the IAS of 0.2%. Before improving the statistical precision further, this requires the systematic uncertainty to be comparable or lower than the statistical uncertainty obtained so far. The efforts we have done over the last years were devoted to the improvement of setup efficiencies (transport, detection for beta particles and protons), but also to decrease the systematic uncertainties. In our 2018 experiment [5], we found that the leading errors were (i) the positron backscattering in the catcher (21e-3 on $a_{\beta\nu}$), the proton detector calibration (9e-3), the beta detection threshold (8e-3), the silicon dead layer thickness (5e-3), the position of the radioactive sample (3e-3), the Mylar catcher foil thickness (2e-3), and the backscattering from the beta detector (2e-3). Four other sources of systematic uncertainties identified were at a level of 1e-3 or lower.

We have improve on all these systematic error sources. The thickness of the catcher foil was reduced by almost a factor of 10 to reduce backscattering. The exact thickness was measured with RBS on the AIFIRA accelerator of Bordeaux with a precision of a few percent (still to be evaluated completely). The proton detector calibration is now performed with a new method allowing to include all measurements (^{32}Ar, ^{33}Ar, thin catcher foil, tests with a thicker catcher foil) at the same time. This should make the contribution negligible. To lower the beta detection threshold, we use now a matrix of nine Si-PMs, which allows us to reduce significantly the threshold and thus its uncertainty. We added also a position-sensitive MCP detector to determine exactly the position and the size of the radioactive sample. Finally, we tested the GEANT4 backscattering models with off-line measurements with a ^{207}Bi source and found that the Goudsmit-Saunderson model is the best model implemented in GEANT4 reproducing well our data.

The systematic uncertainty is still under investigation with the analysis work being carried out presently. A quantitative value is hard to estimate for the moment. However, we expect that the lead systematic error sources should be decreased by a factor of ten or more. E.g. the biggest error from backscattering from the catcher foil should be reduced drastically due to the reduction by a factor of 10 of the foil thickness. In a rough estimate, we believe that we can reach a systematic uncertainty, which should lay between 0.1 and 0.2%, if not better. Therefore, it makes sense to improve also on the statistic uncertainty, which is the purpose of the present addendum.

If we find during the analysis that our systematic uncertainties are much bigger than expected, we would not redo the ^{32}Ar experiment, but rather like to use part of the beam time allocated to make a test with ^{8}Li decay in WISArD. ^{8}Li decays by beta-delayed two-alpha decay. The kinematics of the two alpha particles contains information on the beta-neutrino angular correlation like the proton in the case of ^{32}Ar. The decay of ^{8}Li is a pure Gamow-Teller decay and allows thus the search for exotic tensor currents. ^{8}Li decay gives presently the best limit for tensor contributions. The production rate of ^{8}Li is by far high enough for our experiment. No development is needed to perform this test. The experimental setup would be exactly the same as for the ^{32}Ar experiment.

3. Beam time request

In the May 2024 experiment, we have shown that our equipment performs online as expected and allows the collection of a large sample of ^{32}Ar decay to reach a statistical precision of $a_{\beta\nu}$ and b of the order of 0.1-0.2%, as anticipated in the original proposal. We therefore ask for 24 shifts to have a new run with a combined statistics of 20-30 * 10^{6} decay of the IAS. If the systematic uncertainties for the ^{32}Ar experiment performed in May 2024 would turn out to be much larger than anticipated, we would not run ^{32}Ar again, but rather use a small number of shifts (typically 9) to test the feasibility of a similar experiment with ^{8}Li.

Summary of requested additional shifts: 24 shifts

References

[1] N. Severijns, M. Beck, O. Naviliat-Cuncic, Rev. Mod. Phys. 78, 3 (2006)
[2] M. Gonzalez-Alonso, O. Naviliat-Cuncic, N. Severijns, Prog. Part. Nucl. Phys 104, 165 (2019)
A. Falkowski, M. González-Alonso, O Naviliat-Cuncic, J. High En. Phys. 4, 126 (2021)
M.T. Burkey et al., Phys. Rev. Lett. 128, 202502 (2022)
[3] E.T.H. Clifford et al., Nucl. Phys. A493, 293 (1989)
[4] E. G. Adelberger et al., Phys. Rev. Lett. 83, 1299 (1999)
[5] V. Araujo-Escalona et al., Phys. Rev. C 101, 055501 (2020)
[6] D. Atanasov et al., Nucl. Instrum. Meth. A1050, 168159 (2023)

Details for the Technical Advisory Committee

4.1 General information

Describe the setup which will be used for the measurement. If necessary, copy the list for each setup used.

☒ Permanent ISOLDE setup: *WISArD*

☒ To be used without any modification

☐ To be modified: *Short description of required modifications.*

☐ Travelling setup (*Contact the ISOLDE physics coordinator with details.*)

☐ Existing setup, used previously at ISOLDE: *Specify name and IS-number(s)*

☐ Existing setup, not yet used at ISOLDE: *Short description*

☐ New setup: *Short description*

3.2 Beam production

- Requested beams:

Isotope	Production yield in focal point of the separator (/μC)	Minimum required rate at experiment (pps)	$t_{1/2}$
Isotope 1	^{32}Ar	3000	100 ms
Isotope 2	^{8}Li	10000	840 ms

- Full reference of yield information: *yield database*
- Target - ion source combination: nano-structured CaO with VADIS for 32Ar, surface ionisation with Ta target for ^{8}Li
- RILIS? no

☐ Special requirements: (*isomer selectivity, LIST, PI-LIST, laser scanning, laser shutter access, etc.*)

- Additional features?

☐ Neutron converter: (*for isotopes 1, 2 but not for isotope 3.*)

☐ Other: (*quartz transfer line, gas leak for molecular beams, prototype target, etc.*)

- Expected contaminants: *N14+N18 molecules for ^{32}Ar, can they be laser ionised to 2+ to remove them?*

- Acceptable level of contaminants: as little as possible
- Can the experiment accept molecular beams? Neither for ^{32}Ar nor ^{8}Li
- Are there any potential synergies (same element/isotope) with other proposals and LOIs that you are aware of? no

3.4 Shift breakdown

Summary of requested shifts:

With protons	Requested shifts
Yield measurement of isotope 1 Optimization of experimental setup using isotope 2 Data taking, isotope 1	1 1 22
Without protons	Requested shifts
Stable beam from REX-TRAP or ISOLDE (before run)	1-2

3.5 Health, Safety and Environmental aspects

3.5.1 Radiation Protection

- If radioactive sources are required:
  - Purpose : calibration
  - Isotopic composition: 90Sr, 207Bi
  - Activity : a few kBq
  - Sealed
- For collections:
  - Number of samples?
  - Activity/atoms implanted per sample?
  - Post-collection activities? (*handling, measurements, shipping, etc.*)