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Precise measurement of the angular correlation parameter $a_{\beta\nu}$ in the β decay of ^{35}Ar with LPCTrap

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Abstract. Precise measurements in the β decay of the ^{35}Ar nucleus enable to search for deviations from the Standard Model (SM) in the weak sector. These measurements enable either to check the CKM matrix unitarity or to constrain the existence of exotic currents rejected in the V-A theory of the SM. For this purpose, the β-ν angular correlation parameter, $a_{\beta\nu}$, is inferred from a comparison between experimental and simulated recoil ion time-of-flight distributions following the quasi-pure Fermi transition of $^{35}Ar^{1+}$ ions confined in the transparent Paul trap of the LPCTrap device at GANIL. During the last experiment, 1.5×10^6 good events have been collected, which corresponds to an expected precision of less than 0.5% on the $a_{\beta\nu}$ value. The required simulation is divided between the use of massive GPU parallelization and the GEANT4 toolkit for the source-cloud kinematics and the tracking of the decay products.

1 Introduction

Physics beyond the Standard Model (SM) may be searched through high or low energy experiments [1]. This paper will focus on the latter case and more specifically on observations of β decay processes. The SM is built on many assumptions, including the V-A character of the weak interaction, the maximal violation of parity and the time reversal invariance conservation. Furthermore, the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix is expected to be unitary.

The experiments conducted with the LPCTrap device aim to increase the constraints on the V-A assumption and to test the CKM matrix unitarity. Both may be done through a measurement of the β-ν angular correlation parameter ($a_{\beta\nu}$) value in nuclear β decay. On the one hand, the most general β decay hamiltonian includes scalar and tensor currents associated with Fermi (F) and

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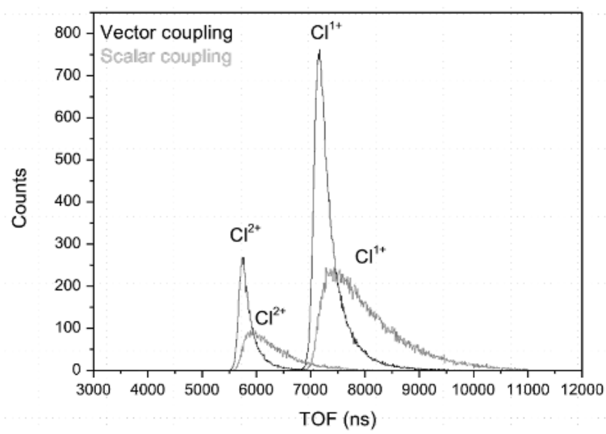

Figure 1. A simulated TOF spectrum of the recoiling Cl daughter ion with two different values of $a_{\beta\nu}$ and two different charge states.

Gamow-Teller (GT) transitions, respectively. Any observed deviation from the $a_{\beta\nu}$ value given by the V-A theory (equal to 1 for F transitions/vector current and -1/3 for GT transitions/axial-vector current) would sign the existence of such exotic currents. On the other hand, one can infer an $a_{\beta\nu}$ value from observed mirror transitions and, assuming that the V-A theory is correct, calculate the mixing ratio of a given transition. The value of the V_{ud} term in the CKM matrix can be deduced if the half-life, branching ratio and masses involved in the decay are also well known [2]. The constraint on the unitarity of the CKM matrix is enhanced each time a V_{ud} value measured with high precision is added to the global database.

The energy distribution of the recoiling daughter ion is sensitive to $a_{\beta\nu}$. To reach this observable, it is not possible to use classical calorimetry since the recoil ions have a very low kinetic energy (a maximum of 450 eV in the case of ^{35}Ar). This is why time-of-flight (TOF) measurements were chosen, where the detection of the ultrarelativistic β particle signals the start while the recoil ion detector provides the stop. To infer $a_{\beta\nu}$ from the data, the TOF distribution is fitted with a linear combination of two simulated spectra (V-A theory value and exotic current value for each transition) [3]. The analysis of the TOF distribution shape thus yields a value for $a_{\beta\nu}$. In addition, the integral under each charge-state peak provides worthy information on the shakeoff processes following the β decay (see figure 1). LPCTrap has proven to be reliable regarding such measurements as shown in previous analysis [4] [5]. The shakeoff is especially important for the ^{35}Ar^{1+} ion study since its sole β^+ decay leads to a neutral ^{35}Cl species, nearly impossible to detect.

2 Preliminary experimental results with the ^{35}Ar nucleus

The SPIRAL1-GANIL facility produces the ^{35}Ar^{1+} ions of interest through the fragmentation of a primary ^{36}Ar beam in a thick graphite target at 95 MeV/A. This radioactive beam is then steered to the LPCTrap at 10 keV with a typical intensity of 3.5×10^7 s^{-1} (~ 5.5 pA). Stable contaminants with the same m/q ratio are dominant with an intensity of 40 pA. The LPCTrap device operates using a transparent Paul trap to confine the radioactive source [6]. One cannot inject directly a continuous beam into such a trap: it first needs to be cooled and bunched. A few steps are required in order to

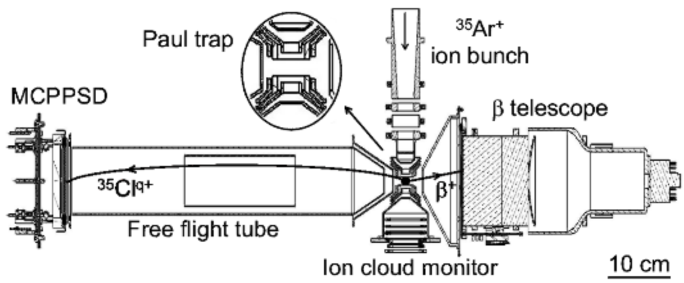

Figure 2. The detection setup scheme, with the MCPPSD on the left, the β telescope on the right and the Paul trap in the center of the chamber.

prepare the ions of interest. LPCTrap functions on a cycle basis: each 200 ms, a new $^{35}Ar^{1+}$ ion bunch is injected in the Paul trap and is ejected after 160 ms, allowing a 40 ms measurement of the background. This implies a thorough tuning of all the device's timings. The beam first enters a RFQCB[1] which is mounted on a 10 kV platform and filled with helium as buffer gas at a pressure of 1.6×10^{-2} mbar to cool the ions. A dynamic quadrupole potential radially confines the ions which are led by a static potential to the end of the RFQCB where bunches are created. Theses bunches are ejected from the RFQCB by switching the static potential each 200 ms. After exiting the RFQCB, they travel through a pulsed drift tube (PD1) and leave it with an energy of about 1 keV, allowing to drive them towards the Paul trap about two meters downstream. A second pulsed drift tube (PD2) slows the bunch to about 100 eV just before the trap. Transmission loss during the preparation stage and contaminant space charge effects lead to 1.5×10^{5} ions trapped each cycle. This number includes both the $^{35}Ar^{1+}$ ions (about 2.5×10^{4} ions bunched in the RFQCB each cycle during the last experiment) and the contaminants.

The detection system is divided into two face-to-face devices around a central Paul Trap as shown in figure 2 [7]. On one side, the β particle is detected by a β telescope (TOF start) consisting in a DSSSD[2] and a plastic scintillator while on the other side the recoil ion is detected with a MCPPSD[3] (TOF stop). The β telescope provides the β particle energy and position. On the MCPPSD side, a first post-acceleration potential at the entrance of a free flight tube enables charge states separation and is followed by a focalization lens to ensure an equal charge-state collection efficiency. A second potential in front of the MCPPSD allows to reach the detection efficiency plateau which is above 3 keV, a higher value than the maximal recoil energy. Other important parameters for the study of the systematic effects are collected, in particular the cycle reference time and the radiofrequency phase.

During the last experiment, 1.5×10^{6} real coincidences were recorded. Summing up both the statistical and estimated systematic effects uncertainties (see section 3), one can expect the precision on the final value of $a_{\beta\nu}$ to be less than 0.5%. The shakeoff measurement on the daughter chlorine led to interesting results [5]. A comparison between the experimental data and theoretical atomic calculations including and excluding the Auger effect was performed. A good agreement was found when considering the Auger effect to reproduce the experimental charge-state branching ratios.

[1]RadioFrequency Quadrupole Cooler Buncher
[2]Double Sided Silicon Stripped Detector
[3]MicroChannel Plate Position Sensitive Detector

3 Simulations

A realistic MC simulation precisely reproducing the measurement conditions is needed. It has to describe precisely the geometry of the detection chamber, the β decay starting vertexes (ion cloud) and full kinematics, the tracking of both the β particle and the recoil ion and the detectors response function. A previous analysis [8] has shown that two of the main systematic effects on the final $a_{\beta\nu}$ value are the proper modelization of the ion cloud and the scattering of the β particle.

Regarding the ion cloud, two specific efforts are done: the modelization of both the localization of each $^{35}Ar^{1+}$ ion in the Paul trap as a function of time and the β decay kinematics. To precisely modelize the cloud made of a few 10^4 ions, massive GPU parallelization happens to be very convenient when including space charge interaction and radiofrequency trapping. Nvidia's CUDA/Thrust [9] was chosen for the computation at a very high speed, along with Boost's ODEINT [10] to integrate the equation of motion. Preliminary tests showed that a few order of magnitude were gained in terms of computing time. For the β decay itself, one needs to take into account that the daughter ^{35}Cl nuclei are in different charge states due to shakeoff and that they may find themselves in an excited state. An appropriate β decay generator has been built, which fully describes the β decay with a dependance on $a_{\beta\nu}$ and includes the γ emission from the two most probable excited states.

The scattering of the β particle is achieved using the latest version of GEANT4 which is expected to better account for low energy processes ($\lesssim$ 5 MeV β particle). The LPCTrap group started a new simulation from scratch using the modular Bayeux/Cadfael package developped by the SuperNEMO collaboration [11] which will be used to wrap GEANT4 and other tools.

4 Conclusion

The LPCTrap device has been used for almost ten years and it provided interesting data [3] [4] [5] [8] [7]. Two of the major systematic effects are being addressed using new and powerful computing tools. The analysis of the last experiment performed in June 2012 with $^{35}Ar^{1+}$ is ongoing and is expected to yield a precise result for the $a_{\beta\nu}$ value at the half-percent level. A new ^{19}Ne experiment will take place during the autumn. With a Q_{EC} value of about 3 MeV, allowing a maximum recoiling energy of 200 eV, and a $T_{1/2}$ value of 17.22 seconds, this experiment will allow testing the limits of LPCTrap. Daniel Rodriguez acknowledges support from the Spanish Ministry of Economy and Competitiveness under the project FPA2010-14803 and the action AIC10-D-000562.

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