EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Precision measurement of the half-life and branching ratio of the T=1/2 mirror β decay of ^{37}K

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Abstract:

We propose to study the T=1/2 mirror β decay of ^{37}K. Nuclear mirror β decay is a competitive mean to test the electroweak model by means of the high-precision measurement of V_{ud} element of the CKM quark mixing matrix. One key ingredient to obtain V_{ud} is the force of the transition, Ft, which has to be determined with a relative precision below 10^{-3}. This quantity is related to the half-life $T_{1/2}$ of the decaying nucleus, the branching ratio BR for this decay and the mass difference between the mother and daughter nucleus (Q value). Another important feature is the mixing ratio ρ between Fermi and Gamow-Teller character of the transition. In most cases, ρ is the major contributor to the uncertainty on Ft. Available data concerning $T_{1/2}$ and BR of ^{37}K suffer from a lack of precision that will be easily reduced by a dedicated experiment.

Requested shifts: 16 shifts

1 Motivation:

The nuclear β decay is an ideal laboratory to study the underlying fundamental symetries of the *standard model* (SM) at low energies. In particular, the nuclear β^+ decay is a purely weak process in which a proton (two up quarks and one down, *uud*) decays to become a neutron (one up quark and two down quarks, *udd*) plus a positron e^+ and an electron-type neutrino ν_e. According to SM, an up quark disappears in this process and a down quark and a virtual W+ boson is produced. The W+ boson then decays to produce a e^+ and a ν_e. The β^+ decay is thus a semi-leptonic strangeness-conserving process inherently sensitive to the physics of the weak interaction, and small deviations of experimental results from SM predictions translate directly into new physics beyond SM.

The relative strength of the weak interaction in pure leptonic, semi-leptonic and in pure hadronic processes has been incorporated into the electroweak theory by the quark mixing. In the case of the three quark families, the mixing is expressed by means of the Cabibbo-Kobayashi-Maskawa (CKM) [1] matrix. The CKM-matrix relates the quark weak interaction eigenstates to the quark mass eigenstates and, as such, the normalization of the states requires the CKM-matrix to be unitary.

Up to now only the matrix elements V_{ud} and V_{us} have been determined with a precision of a 10^{-3} level and thus the most precise test of the unitarity to date is obtained from the first row of the CKM-matrix, *i.e.* $V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 1$. The dominant input is the up-down element (V_{ud}) that has been most precisely determined from super-allowed pure Fermi transitions [2]. However it has been recently pointed out [3] that nuclear mirror transitions between T=1/2 isospin doublets, offer an additional source to determine V_{ud} and thus to test the unitarity of the CKM matrix. Such a source is then complementary to pure Fermi ($0^+ \rightarrow 0^+$) transitions, neutron decay and pion decay.

The SM incorporates the conserved-vector-current (CVC) hypothesis, which assumes that the vector part of the weak interaction is not influenced by the strong interaction. Thus, the vector coupling constant g_V is not renormalized in the nuclear medium. If CVC is verified, a universal comparative half-life $\mathcal{F}t$ value, which depends only on the isospin of the decaying nucleus, gives acces to g_V. $\mathcal{F}t$ is determined from the experimental ft values (where "f" is the statistical rate function and "t" the partial halflife) after applying the theoretical corrections which are necessary due to isospin impurities of the nuclear states, nuclear structure differences impacting on radiative corrections as well as nucleus dependent and nucleus independent radiative corrections (see ref. [2] and references therein for a review). For mirror β decay of T=1/2 nuclei $\mathcal{F}t$ is given by:

$$\mathcal{F}t = \frac{k}{g_v^2} \times \frac{1}{< M_F >^2 (1 + \Delta_R)(1 + (f_a/f_v)\rho^2)}$$

where k is a product of constants and $< M_F >$ is the Fermi-decay matrix element with $< M_F >^2 = T(T+1) - T_{zi}T_{zf}$. T is the isospin of the decaying nucleus and T_{zi} and T_{zf} are the third components of T for the initial and final state. f_v and f_a are the statistical rate function for vector and axial-vector currents respectively, ρ is the Gamow-Teller to Fermi mixing ratio and Δ_R is the nucleus independent radiative correction. Once CVC is verified, the vector coupling constant g_V together with the muonic vector coupling constant, allow for the determination of the V_{ud} element of the CKM-matrix. V_{ud} as determined from mirror transitions is 0.9719(17) [3]. This value results from a compilation of existing data without any dedicated experiment carried out motivated by this physics.

Improving and extending the data already available for mirror transitions would allow building a new database with a sensitivity comparable to the pure Fermi transitions. Initially both databases will serve as cross-checks for each other, while later an overall analysis of all data will enable to improve significantly the sensitivity for new physics. Many interesting mirror transitions exist and the improvement in precision of the relevant data appears easily reachable. This requires the measurements of half-lives ($T_{1/2}$), branching ratios (BR) and masses of the involved nuclei, as in the case of pure Fermi transitions, but also the measurements of correlation observables to precisely determine the Gamow-Teller to Fermi ratios (ρ) [4].

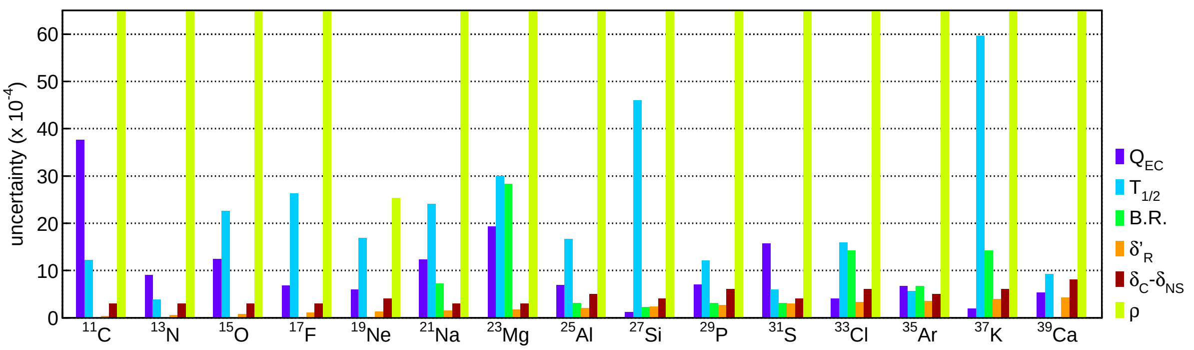

Figure 1: *Histogram of the fractional uncertainties attributed to each experimental and theoretical input factor that contributes to the final Ft mirror values taken from [5] and updated to the data available in 2011.*

A summary of the relative errors on the different experimental and theoretical inputs values [5] needed to calculate the corrected comparative half-lives are presented in Figure 1. In most cases, ρ is the major contributor to the uncertainty on Ft. Available data concerning $T_{1/2}$ and BR of ^{37}K suffer from a lack of precision that should be easily reduced by a dedicated experiment. Therefore, in the general trend to review mirror transitions for high precision measurements, ^{37}K is a priority target.

2 Experimental details and beam-time request

2.1 Production of ^{37}K at ISOLDE

^{37}K will be produced by bombarding a 40 g/cm^2 Ti-Metal-foil target with 0.6 GeV protons from the CERN PS Booster [6]. The potassium atoms will be ionized on a hot tungsten surface, accelerated to 60 keV, passed through the High Resolution Separator HRS and transported to the detection setup placed at the end of LA1 beamline. The expected rate of ^{37}K is 7.1E+06 ions/μC [6]. The only expected contaminant is ^{37}Ca since with such ion source, the production of an argon ion beam is impossible.

2.2 The half-life and branching ratio measurement

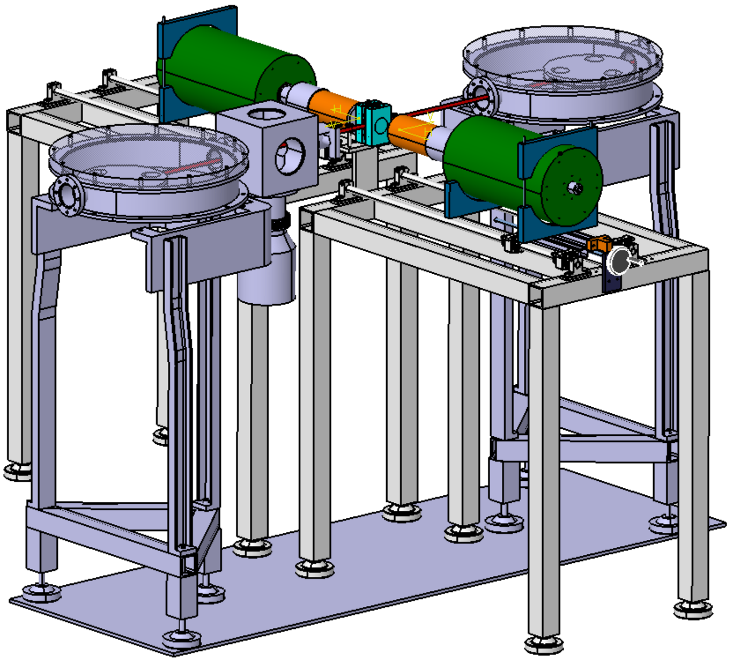

Figure 2: *Experimental setup as used in the ISOLDE 2007 experiment to measure the half-life of* ^{38}*Ca.*

The detection setup will consist of a tape transport station and a β-detection setup surounded by two γ detectors (see Figure 2). The electronics will work with a fixed dead-time per event which is much longer than any possible delay from the electronics or the data acquisition. Three independent data acquisition systems with different dead-times (2, 8 and 100 μs) will be used. The first two acquisitions will be a simple but very fast single-channel system which will store each measurement cycle-by-cycle, whereas the third acquisition will allow for an event-by-event listmode data acquisition. This later one will be used also for the γ detection.
The measuring cycle will be as follows: first the ^{37}K activity will be accumulated on a tape during 1 s. As the only expected contaminant will be ^{37}Ca ($T_{1/2}$=181.1 (10) ms [7]) if we let decay the activity for about 2 half-lives of ^{37}K ($T_{1/2}$=1.226(7) s [7], so during 2.5 s, corresponding to about 14 half-lives of ^{37}Ca) almost all the ^{37}Ca will be already gone and thus no contaminants are expected during the decay-measuring time. Then the activity will be transported to the β-detection setup. The β decays will be measured for 20 half-lives by a 4π high-efficiency β gas detector. After this measuring time, the tape is moved to discard the rest of radioactivity and a new cycle starts. These cycles will be repeated until the desired statistics is achieved. Cycles with different experimental conditions like trigger thresholds, or detector high voltages will form different runs.

Figure 3 shows the decay scheme of ^{37}K. The strongest γ ray in its decay (2796 keV) has a branching ratio of 1.8%. Absolute branching ratios will be obtained by normalising the γ rays with the number of β decays observed with β gas counter. In fact to remove the uncertainty due to the β detection efficiency, decay events will be triggered only by the β detection system.

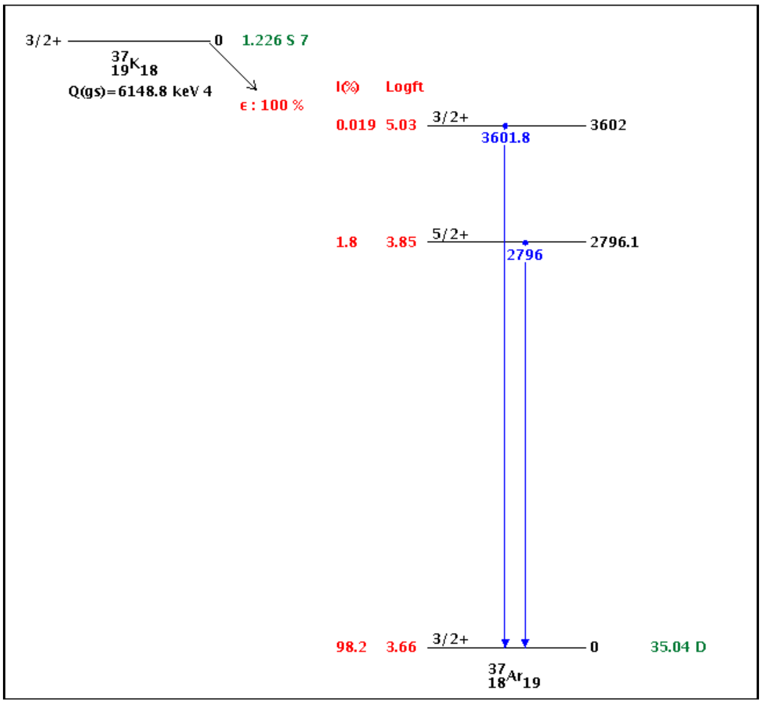

Figure 3: *Decay schme of* ^{37}*K [7].*

2.3 Estimation of the number of beam shifts required

The aim of this work is to achieve a high-precision measurement of the half-life and BR with an error below 0.1%. To make sure that the statistical errors are below this level, we aim for the detection of 10^7 ^{37}K decays.

For the half-life measurements, with beam-on beam-off cycles, and in order to control the dead-time, we consider an effective rate of about 1000 ^{37}K decays detected during the decay-measuring time. We consider 20 h of effective measuring time per day, and hence 2.6x10^6 ^{37}K decays will be accumulated per day((1000 counts/cycle)*(1 cycle/28 s)*(72000 s/day)). Within 3 days (9 shifts) a total of about 7.7x10^6 ^{37}K decays will be accumulated. To make sure that the result obtained is not biased by any experimental parameter (e.g. trigger threshold, decay-measuring time, detector high-voltage, etc), one has to change these parameters during the experiment. 2 days (6 shifts) will be required for such tests. During the 15 shifts a total of 1.3x10^7 ^{37}K decays will be accumulated.

For the branching ratio measurements, as the photo-peak efficiency is about 0.3% at 15cm for the 2796 keV branch, during the half-life measurements an average of 3 counts/cycle will be accumulated. During 5 days of measurements a total of 3.9x10^4 counts will be accumulated, ((3 counts/cycle)*(1 cycle/28 s)*(72000 s/day)*5 days) yielding a relative uncertainty ($\sqrt{N}/N$) of 5x10^{-3}.

Summary of requested shifts:

The overall beam time requested is as follows:

- 1 shift to optimize the production rate, the ISOLDE setting and the purity of the ^{37}K.
- 15 shifts to measure the half-life and the branching ratio of ^{37}K

This yields a total beam time request of 16 shifts.

References

[1] N. Cabibbo, Phys. Rev. Lett. **10** (1963) 531. Kobayashi, M and Maskawa K., Prog. Thor. Phys. **49** (1972) 282.

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[5] N. Severijns et al., Phys. Rev. C **78** (2008) 055501.

[6] *https://oraweb.cern.ch/pls/isolde/*

[7] *http://www.nndc.bnl.gov/*

Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: (*name the fixed-ISOLDE installations, as well as flexible elements of the experiment*)

Part of the	Availability	Design and manufacturing
Setup for β-γ detection. Detectors, supports, electronics, tape station, etc, supplied by collaboration partners.	☒ Existing	☒ To be used without any modification

HAZARDS GENERATED BY THE EXPERIMENT (if using fixed installation:) Hazards named in the document relevant for the fixed [COLLAPS, CRIS, ISOLTRAP, MINIBALL + only CD, MINIBALL + T-REX, NICOLE, SSP-GLM chamber, SSP-GHM chamber, or WITCH] installation.

Additional hazards:

Hazards	β-γ detection setup.	[Part 2 of experiment/ equipment]	[Part 3 of experiment/ equipment]
Thermodynamic and fluidic			
Pressure	-		
Vacuum	Standard ISOLDE vacuum		
Temperature	-		
Heat transfer	-		
Thermal properties of materials	-		
Cryogenic fluid	LN_2 cooling of Ge detectors		
Electrical and electromagnetic			
Electricity	3 kV (Ge detectors)		
Static electricity	-		
Magnetic field	-		
Batteries	-		
Capacitors	-		
Ionizing radiation			
Target material	-		
Beam particle type (e, p, ions, etc)	^{37}K		
Beam intensity	10^5 to 10^3 ions/s		
Beam energy	60 keV		
Cooling liquids	LN_2		
Gases	P5 95% Ar, 5% CH4		

Calibration sources:	☒		
• Open source	☐		
• Sealed source	☒ [ISO standard]		
• Isotope	$^{60}Co, ^{137}Cs, ^{152}Eu, ^{133}Ba, ^{90}Sr$		
• Activity	$\leq$ 40 kBq		
Use of activated material:			
• Description	☐		
• Dose rate on contact and in 10 cm distance	-		
• Isotope	-		
• Activity	-		
Non-ionizing radiation			
Laser	-		
UV light	-		
Microwaves (300MHz-30 GHz)	-		
Radiofrequency (1-300 MHz)	-		
Chemical			
Toxic	-		
Harmful	-		
CMR (carcinogens, mutagens and substances toxic to reproduction)	-		
Corrosive	-		
Irritant	-		
Flammable	-		
Oxidizing	-		
Explosiveness	-		
Asphyxiant	-		
Dangerous for the environment	-		
Mechanical			
Physical impact or mechanical energy (moving parts)	-		
Mechanical properties (Sharp, rough, slippery)	-		
Vibration	-		
Vehicles and Means of Transport	-		
Noise			
Frequency	-		

Intensity	-		
Physical			
Confined spaces	-		
High workplaces	-		
Access to high workplaces	-		
Obstructions in passageways	-		
Manual handling	-		
Poor ergonomics	-		

Hazard identification:

Negligible.