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Precision measurement of the half-life of the superallowed $0^+ \rightarrow 0^+$ β decay of ^{38}Ca

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Abstract

A first study of the half-life of ^{38}Ca was performed at ISOLDE in may 2006, where a preliminary half-life of 451.8(16) ms was obtained. In parallel, the mass excess of this isotope was measured with the new Ramsey technique. The somewhat modest precision obtained for the half-life of about 4×10^{-3} is due to a strong loss of production rate after the first 6 hours. This was most likely due to a melting of the titanium target as a consequence of a too strong beam focussing. About a week of beam time under normal conditions should allow for a determination of the half-life with a precision of 1×10^{-3}. At a later stage, a measurement of the branching ratio of the super-allowed decay is also forseen.

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1 Introduction

Superallowed $0^+ \rightarrow 0^+$ β decays are compelling because of their simplicity. The axial-vector decay strength is zero for such decays, so the measured ft values are directly related to the weak vector coupling constant through the following equation [1]:

$$Ft = ft(1 + \delta'_R)(1 + \delta_{NS} - \delta_c) = \frac{K}{M_F^2 G_V'^2} \quad (1)$$

where K is a known constant, G'_V is the effective vector coupling constant and M_F is the Fermi matrix element between analogue states. Radiative corrections, δ'_R, modify the decay rate by about 1.5% and structure-dependent corrections (δ_c, δ_{NS}) modify the "pure" Fermi matrix element by about 0.5-1%. Figure 1 shows these Ft values for the most precisely measured values.

Accurate experimental data on Q_{EC}-values, half-lives and branching ratios combined with the three correction terms permit precise tests of the Conserved Vector Current (CVC) hypothesis, via the constancy of Ft values, irrespective of the $0^+ \rightarrow 0^+$ decay studied [1]. The CVC test achieved through these nuclear physics experiments is currently far superior to any particle physics tests [1, 2]. At present, the best hopes for further improvements are also in the field of superallowed β decay.

These data also yield a value for G'_V which, in combination with the weak vector coupling constant for the purely leptonic muon decay, provides a value for V_{ud}, the up-down quark mixing element of the CKM matrix. Together with the smaller elements, V_{us} and V_{ub}, this matrix element provides a stringent test of the unitarity of the CKM matrix.

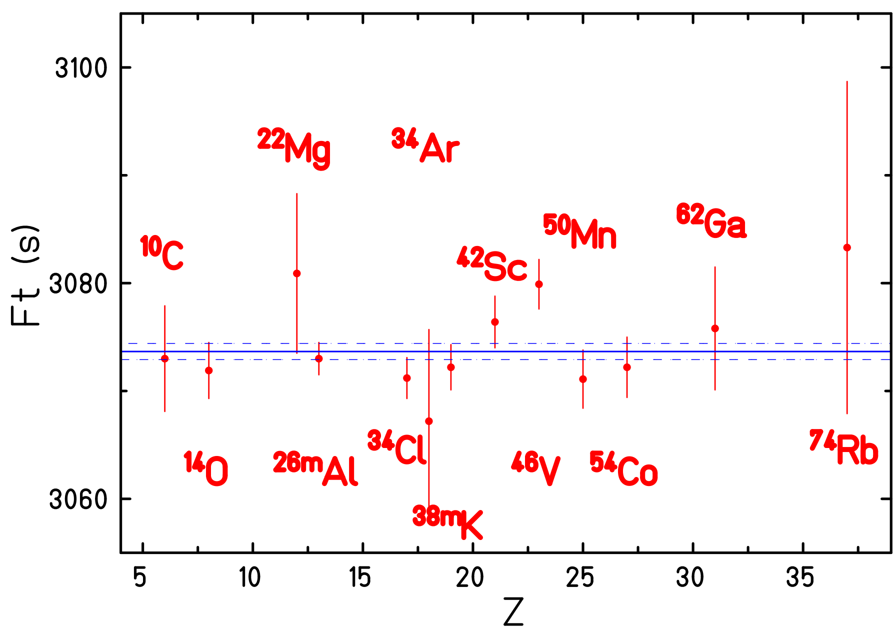

Figure 1: *Ft value as compiled by Hardy and Towner [1] completed with recent results.*

V_{ud} is the most precisely known element of the CKM matrix [3] but, because of its large size, also the largest contributor of the uncertainty in unitarity tests of the first row and the first column of the CKM matrix. It is therefore important to improve the precision of V_{ud}. The existing data set of superallowed β emitters can be improved and enlarged through additional measurements on heavier or more exotic superallowed Fermi emitters.

2 Physics case

The constancy of the corrected Ft values, as seen in Figure 1, indicates that the vector current is indeed conserved, independent of the nucleus it is acting in. The constancy test simultaneously probes the accuracy of the charge-dependent corrections. These nuclear-structure-dependent corrections are considered by many physicists to be the weakest link in the superallowed $0^+ \rightarrow 0^+$ research [4]. In any case, they limit today the precision on the coupling constant G'_V [1].

The corrections calculated for some of the medium-mass T_z = -1 nuclei are unusually large (see Figure 2). The correction factor calculations for these nuclei are believed to be relatively reliable (see error bars in figure 2), as compared to the heavier N=Z nuclei where these corrections are also large, but much more difficult to calculate. However, the T_z = -1 nuclei have in turn the disadvantage of having large non-analogue branching ratios which are difficult to measure with the required precision.

If the corrected Ft values for the new heavier cases as well as for newly measured T_z = -1 nuclei agree with those obtained for the other well-studied decays, then the confidence in the CVC hypothesis and the charge-dependent correction calculations would receive a significant boost. This has been reached partly recently with the determination of Ft for ^{74}Rb [5], ^{62}Ga [6, 7], ^{34}Ar [8], and ^{22}Mg [9, 10]. However, the error bar for some of these Ft values is still rather large and will be difficult to be improved as the measurements have reached their precision limits.

The information we are aiming at in this proposal is the half-life of ^{38}Ca. The half-life of ^{38}Ca has been measured several times in the past [11, 12, 13, 14]. These results together with our results from may 2006 are not sufficient to reach the precision aimed for of better than 1×10^{-3}.

3 Results from the 2006 experiment

The experiment performed in may 2006 allowed us to determine the half-life of ^{38}Ca with a precision of better than 2ms. A preliminary value is 451.8(16) ms. This result has been obtained as the average of 20 different runs. The difference with respect to the precision aimed for of about 1×10^{-3} is mainly due to a drop in production rate by a factor of 3-8 after only 6 hours or 4 runs, most likely due to a melting of the titanium target due to a to strong beam focussing. This can be seen in figure 3a, where the ^{38}Ca count rate at our detection setup per proton pulse is shown. After four runs, we had already obtained almost half of the total statistics (see figure 3b).

In addition, due to the much lower production rate of ^{38}Ca from run 20 on, the background is of much more concern. Indeed, the averaging of all runs yields an average value with a χ^2 of only about 2.5, which may be indicative of a background not completely flat. Such a non-uniform background has a much stronger influence on the data for the

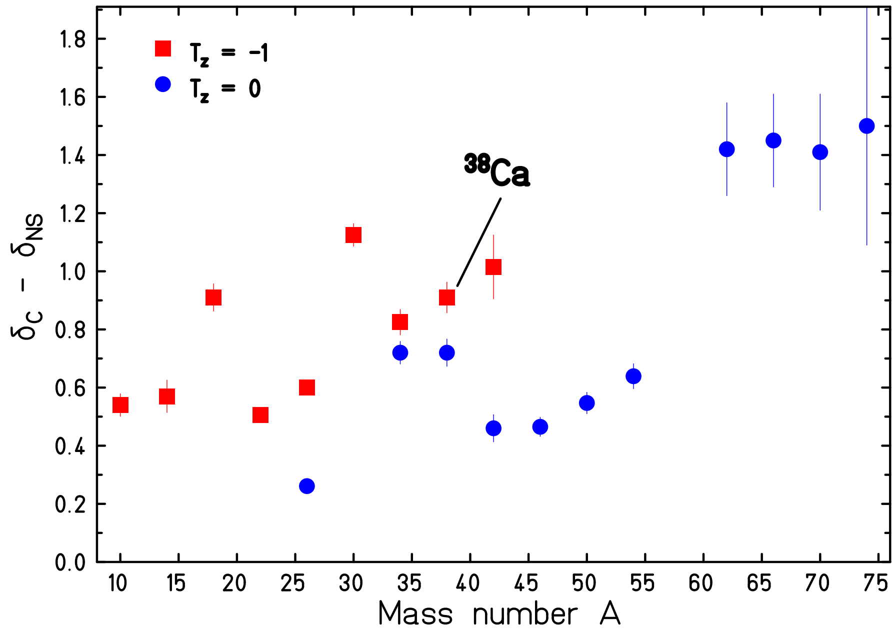

Figure 2: $\delta_c - \delta_{NS}$ *correction factors as calculated by Hardy and Towner [1].*

low-statistics runs than for the first four high-statistics runs. In contrast, the first three runs agree with each other within the limits of their statistical precision.

The half-life measurement took only two out of 13 proton pulses within the PS supercycle. The other proton pulses were used by ISOLTRAP to measure the mass excess of ^{38}Ca. In this experiment, a new frequency scan, the Ramsey scan, was used for the first time for a mass measurement. This measurement yielded a high-precision value for the mass excess of ^{38}Ca [15] in agreement with a recent measurement from MSU [16].

4 Experimental details and beam-time request for a new measurement

4.1 Production of ^{38}Ca at ISOLDE

^{38}Ca will be produced using a titanium foil with a CF4 leak to form CaF^+ molecules. This allows to remove completely ^{38}K, the most troublesome contaminant. The molecules will be surface ionized in a tungsten cavity. As we will not measure in parallel the mass of ^{38}Ca as in the 2006 experiment, the target will receive only the proton pulses used to produce the ^{38}Ca isotopes for the half-life measurement, i.e. one pulse every 7-8 seconds instead every 1.2 seconds. This fact and a beam focalisation more adapted to the titanium target should give a much longer life time to the target.

The $^{38}CaF^+$ molecules will be selected by the HRS and then injected in the REXtrap where they are accumulated. The extraction from the trap allowed for a selection of $^{38}CaF^+$ by time of flight. A fast kicker selected the $^{38}CaF^+$ molecules and rejected any other mass, in particular $^{38}K^+$. The molecules were sent onto a tape which allowed for a transport into the detection setup. The transmission to the trap, of the trap and after the trap as well as the losses due to decay during the tape transport yielded a final rate of

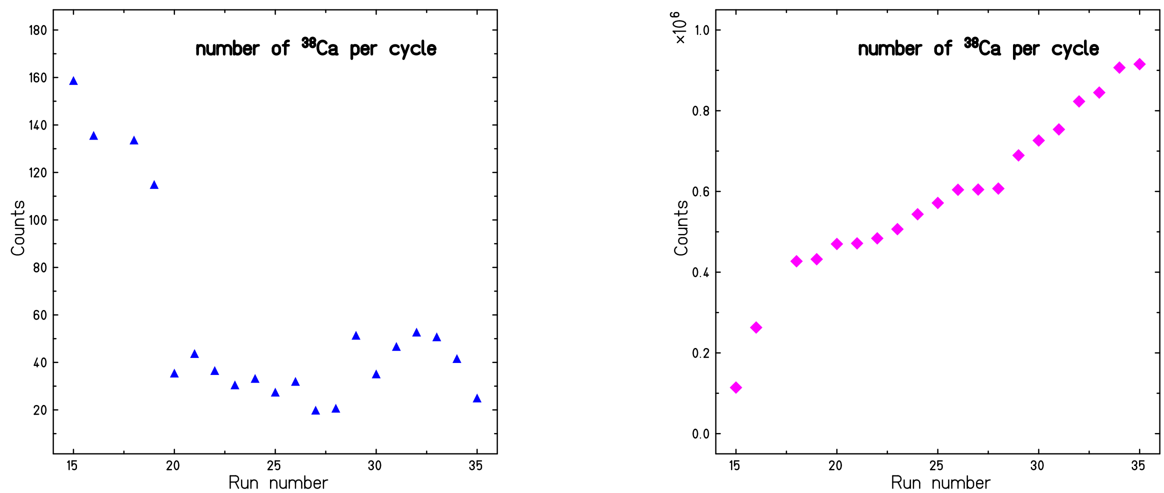

Figure 3: *Preliminary results from the may 2006 experiment. Left: Detection rate of ^{38}Ca at our experiment station per proton pulse. Right: Integrated statistics for the different runs showing that after the first three runs almost half of the statistics was already obtained.*

about 150 ^{38}CaF$^+$ per proton pulse in our setup at the beginning of the experiment. Such a rate is sufficient to perform the high-precision measurements proposed in the present proposal, as long as stable conditions can be maintained for about one week.

4.2 The half-life measurement

As in the may 2006 experiment, the detection setup for the half-life measurement will consist of a tape transport station, a β-detection setup (90% efficiency), and γ detectors (figure 4.2) linked to two independent data acquisition systems. One acquisition will be a simple but very fast single-channel system for the half-life measurement, which will store each measurement cycle individually, whereas the second acquisition will allow for an event-by-event listmode data acquisition. The first data acquisition will allow for a cycle-by-cycle dead-time correction which is needed to achieve the high precision for the half-life. The second DAQ will by used mainly for the γ detection.

The ^{38}CaF$^+$ activity will be selected by the HRS, accumulated for about 2 half-lives in REXtrap and purified either by the time-of-flight as in the 2006 experiment or by an mass-selective excitation with REXtrap. After this, the activity will be transported to the counting station inside a high-efficiency β gas detector, where the decay will be measured for 15 half-lives. After this decay time, a new accumulation starts. The half-life will be determined only from the β particles. The γ detectors serve two purposes: i) to search for impurities present in the ISOLDE beam which have to be included in the half-life fits and ii) to perform a rough determination of the β-decay branching ratios.

Our aim is to perform a high-precision half-life measurement with a half-life error well below the 0.1% level. To make sure that the statistical errors have only a minor contribution to the total error bar, we aim for the detection of 10^7 decays. With the beam-on/beam-off cycles, we will have an effective rate of about 20 counts/second (150 counts per proton pulse with a proton pulse every 7.2 s; in fact we intend to take proton pulse 1 and 7). Therefore, sufficient statistics can be accumulated within five days of

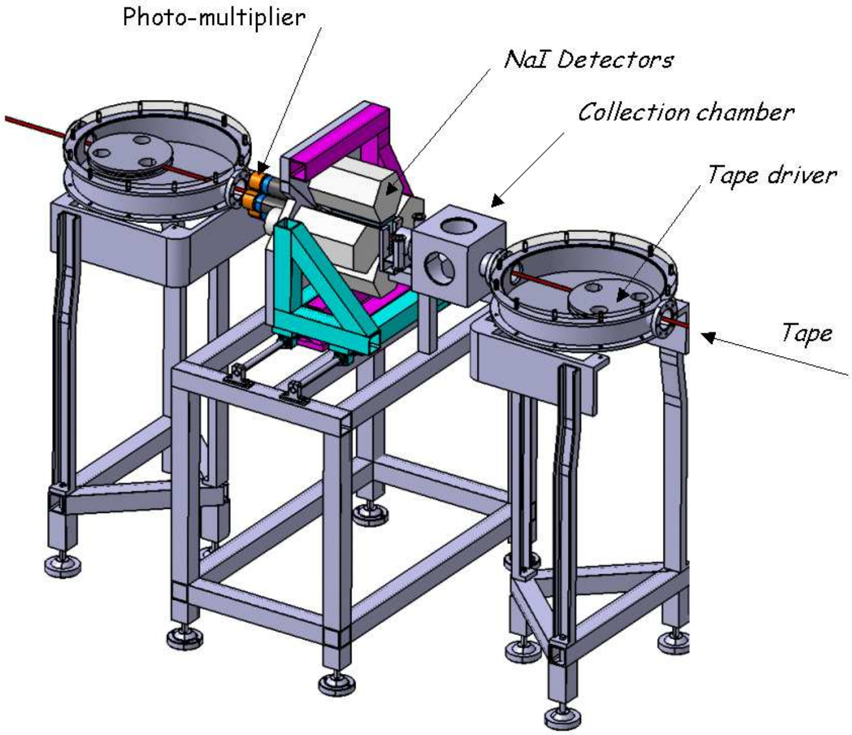

Figure 4: *Experimental setup as used in the ISOLDE 2006 experiment to measure the half-life of* ^{38}Ca.

beam time (about 9×10^6 s, if we assume that the experiment runs with a "duty cycle" of 100%). To make sure that the result obtained is not biased by any experimental parameter (thresholds, high voltages, dead times etc.), one has to change these parameters during the experiment. As in previous experiments (see e.g. [17]), these parameter changes can be performed during the measurements. We intend also to devote 2 shifts to measure the half-life of ^{39}Ca. This nucleus has a twice longer half-life and allows us therefore to check whether calcium is diffusing out of the tape. Such a diffusion would falsen the half-life. In addition, about one shift is needed to optimize the ISOLDE beam.

5 Beam time request

The overall beam time request is as follows:

- 1 shift to optimise the ISOLDE setting
- 15 shifts to measure the half-life of ^{38}Ca with a precision of better than 0.1%
- 2 shifts to measure the half-life of ^{39}Ca

This yields a total beam time request of 18 shifts.

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