Proposal for the ISOLDE facility:

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

A. Bey, B. Blank, G. Cancel, C. Dossat, A. Fleury, J. Giovinazzo, I. Matea
Centre d'Etudes Nucléaires de Bordeaux-Gradignan, F-33175 Gradignan, France

M.J.G. Borge, O. Tengblad, M. Turrion
CSIC Madrid, Spain

J. Äystö, A. Jokinen, A. Kankainen
Accelerator Laboratory, University Jyväskylä, Finland

D. Lunney, C. Guénaut
CSNSM Orsay, Orsay, France

A. Herlert, L. Schweikhard
University Greifswald, Germany

K. Blaum
University Mainz, Germany

P. Delahaye, L. Fraile, C. Yazidjian
CERN, Geneva, Switzerland

F. Herfurth
GSI, Darmstadt, Germany

Abstract

We propose to study the β decay of ^{38}Ca. In a first instance, we intend to perform a high-precision study of the half-life of this nucleus as well as a measurement of its β-decay Q value with ISOLTRAP. At a later stage, we propose to study its decay branches to determine the super-allowed branching ratio with high precision. These measurements are essential to improve our understanding of the theoretical corrections (in particular the δ_c correction factor) needed to calculate the universal Ft value from the ft value determined for individual nuclei. For this nucleus, the correction factor is predicted to increase significantly as compared to the nine well-studied nuclei between ^{10}C and ^{54}Co and the model calculations used to determine the corrections, in particular the shell-model calculations, are well under control in this mass region. Therefore, the T_Z = -1 nuclei between A=18 and A=38 are ideal test cases for the correction factors which limit today the precision on the universal Ft value and therefore on the value of the vector coupling constant and on the V_{ud} matrix element of the CKM quark-mixing matrix.

Spokesperson: B. Blank
ISOLDE contact person: L. Fraile, A. Herlert

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%.

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. At present, the unitarity condition is violated at the two standard deviation level, if one takes the values for V_{us} and V_{ub} as suggested by the Particle Data Group (PDG) [3]. We mention, however, that new measurements [4, 5] seem to indicate that the currently accepted value for V_{us} is too low. Although creating other problems, the newly measured values would restore unitarity for the first row of the CKM matrix at the level of precision achieved today. Other possible origins for the non-unitarity of the CKM matrix span from right-handed currents to additional quark generations.

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 vital to improve the precision of this element. 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

A critical analysis of the sources of a possible non-unitarity of the CKM matrix is important. While the situation for V_{us} has to be clarified, we concentrate here on V_{ud} which falls in the domain of low-energy nuclear physics.

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, in that erroneous predictions would scatter or put a slant to the line through the data points. These nuclear-structure-dependent corrections are considered by many physicists to be the weakest link

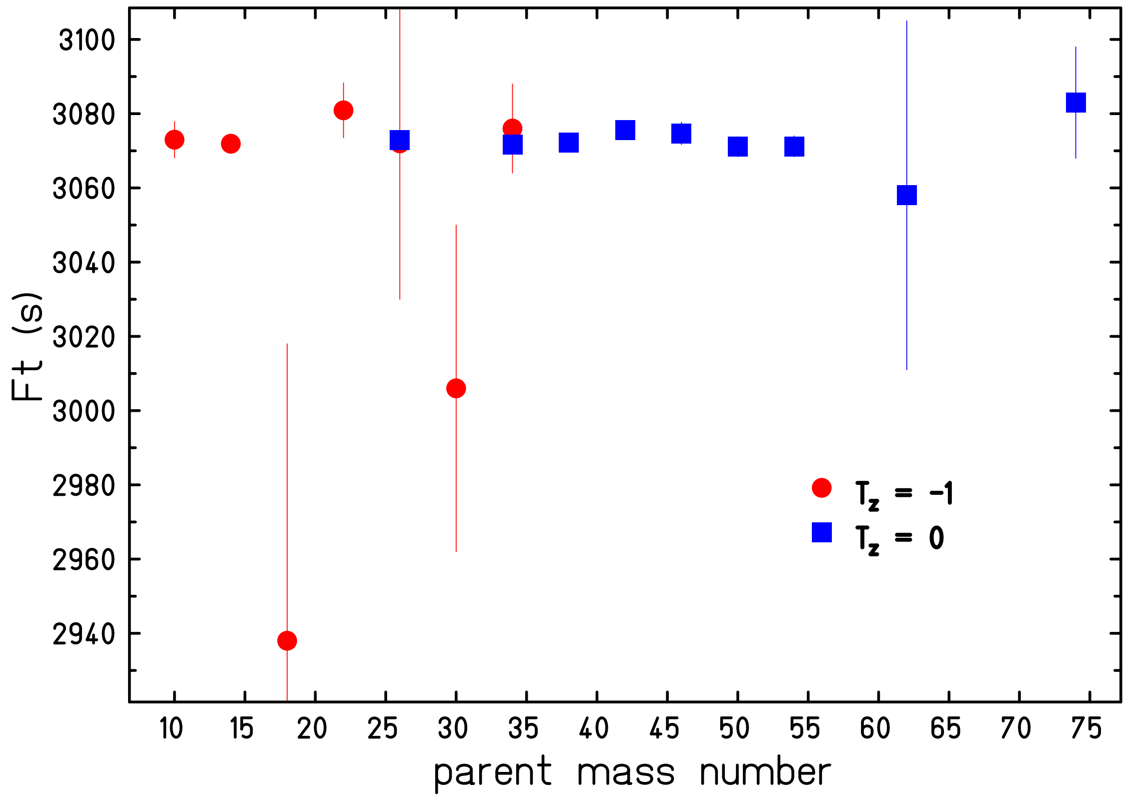

Figure 1: *Ft value as compiled by Hardy and Towner [1].*

in the superallowed $0^+ \rightarrow 0^+$ research [6]. In any case, they limit today the precision on the coupling constant G'_V.

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 nine 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 [7]. However, the error bar for the Ft value of ^{74}Rb is still rather large and will be difficult to improve as the measurements used have reached their precision limits. ^{62}Ga will certainly be the next heavy nucleus to be included in the $0^+ \rightarrow 0^+$ systematics [8, 9, 10]. However, as precision mass measurements for ^{62}Ga and ^{62}Zn are still to be performed, it is not clear, which final precision can be reached. Two other T_z = -1 nuclei have recently reached the order of magnitude precision needed: ^{22}Mg and ^{34}Ar. In both cases, the precision on the branching ratio is a limiting factor. In the case of ^{34}Ar, in addition the half-life has still to be improved, too.

The information we are aiming at in this proposal is the half-life of ^{38}Ca and its β-decay Q value. The half-life of ^{38}Ca has been measured several times in the past [11, 12, 13, 14].

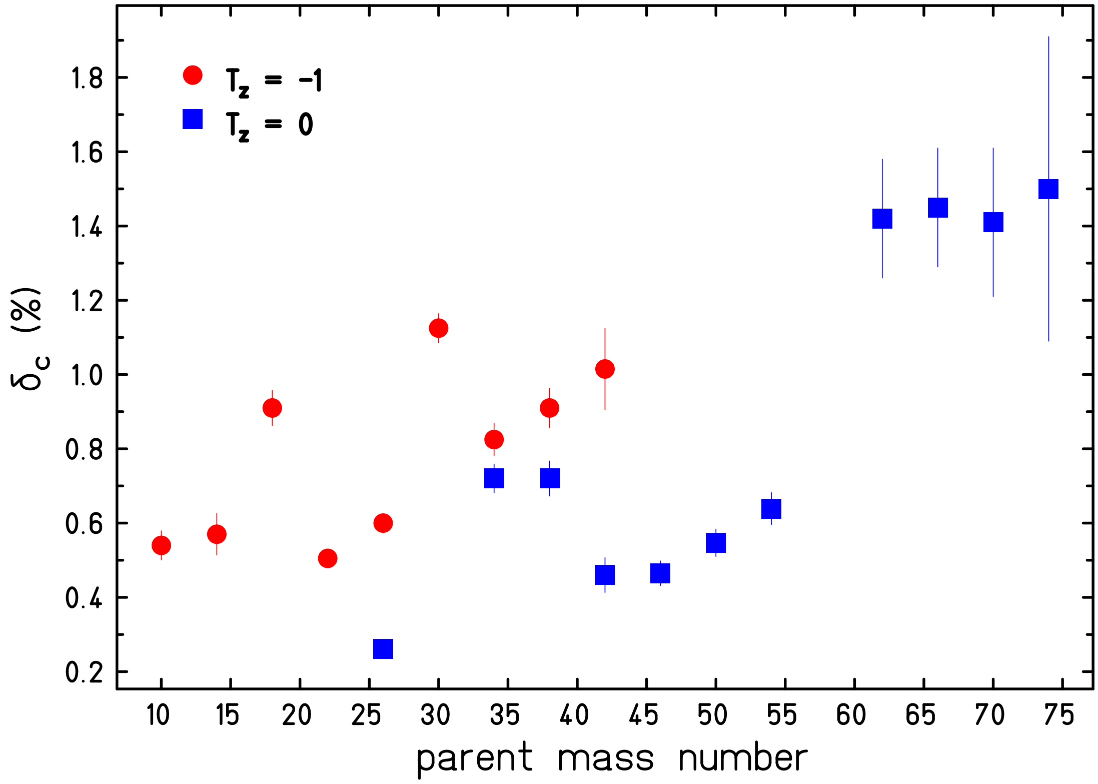

Figure 2: δ_c *correction factors as calculated by Hardy and Towner [1].*

However, these measurements yield error bars which are by far to large to contribute in any way to the subject discussed here. The mass of ^{38}Ca was obtained as a by-product of a ^{42}Ca(p,t)^{40}Ca measurement [15]. However, the precision is only 5 keV, about on order of magnitude larger than needed. No measurement at all exists for the branching ratios.

3 Experimental details and beam-time request

3.1 Production of ^{38}Ca at ISOLDE

^{38}Ca will be produced from 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 W cavity.

The expected production rate of ^{38}Ca is 5×10^3 pps per micromapere of proton beam [16]. With the PSB intensity now available for ISOLDE, a counting rate of about 10000 ^{38}Ca per second can be expected. Due to flourination, about 50% of the intensity is lost and we expect therefore a counting rate of 5000 ^{38}Ca per second. Such a rate is sufficient to perform the high-precision measurements proposed in the present proposal.

3.2 The half-life measurement

The detection setup for the half-life measurement will consist of a tape transport station, a β-detection setup, γ detectors (figure 3 shows the setup used at the online mass separator of GSI [9]) 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}Ca activity will be accumulated for about 2 half-lives (i.e. 2×440 ms which corresponds basically to one proton beam pulse). After this accumulation the activity will be transported to the counting station inside a high-efficiency β detector (either a plastic scintillator or a gas detector), where the decay will be measured for 20 half-lives. After this decay time, a new accumulation starts etc. 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.

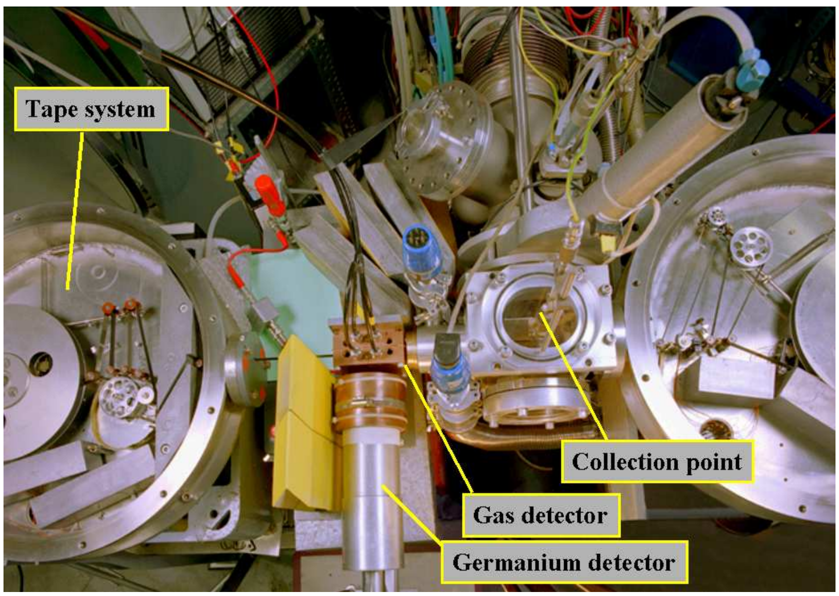

Figure 3: *Experimental setup as used in the GSI experiment to measure the half-life of* ^{62}*Ga with high precision [9].*

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 500 counts/second. Therefore, sufficient statistics can be accumulated within three shifts of beam time (see e.g. [9]). However, to make sure that the result obtained is not biased by any experimental parameter (e.g. trigger threshold, fixed dead time, detector high-voltage etc.), one has to change these parameters during the experiment. We believe that these parameter changes can be performed within six additional shifts. In addition, about one shift is needed to optimize the ISOLDE beam.

3.3 The mass measurement of ^{38}Ca

As mentioned above, the mass of ^{38}Ca is known only with a precision of 5 keV, *i.e.* with a relative mass uncertainty of about $\delta m/m = 1.4 \cdot 10^{-7}$. With the Penning trap mass spectrometer ISOLTRAP, a mass determination with a relative mass uncertainty of the order of $1 \cdot 10^{-8}$ is routinely achieved as shown in the 2004 beam time period [17].

With the intensities expected, the mass of ^{38}Ca can be measured relatively easily. The statistical uncertainty for the determination of the cyclotron frequency is roughly given by $\delta\nu/\nu \approx R^{-1} \cdot N^{-1}$. The resolving power $R = \nu_c/\Delta\nu_c$(FWHM) depends on the width $\Delta\nu_c$(FWHM) $= 0.9/T_{ex}$ of the cyclotron resonance curve, where T_{ex} is the excitation duration in the precision Penning trap. For short-lived radionuclides, a value of $T_{ex} = 3 \cdot T_{1/2}$ is reasonable, which allows in the case of ^{38}Ca ($T_{1/2} = 440$ ms) an excitation time of $T_{ex} = 1.2$ s. For a total number of $N = 3000$ ions this yields a relative uncertainty $\delta\nu_c/\nu_c$ of less than $1 \cdot 10^{-8}$.

The calibration of the magnetic field B is done with the determination of the cyclotron frequency of a nuclide with a well known mass. In case of the ^{38}Ca measurement, this can be stable ^{39}K from the reference ion source of ISOLTRAP, carbon clusters $^{12}C_3$ (with an atomic mass of 36 u) also delivered from ISOLTRAP and possibly ^{38}K from ISOLDE. These masses are within 1-2 mass units of ^{38}Ca and therefore allow a mass determination with a relative mass uncertainty of the order of $1 \cdot 10^{-8}$, *i.e.* an uncertainty of the mass excess of about 0.4 keV, as required.

Isobaric contaminants can be removed from the preparation trap and the precision trap with a resolving power of 10^5 and 10^6, respectively, which is, *e.g.*, in case of ^{38m}K no problem, where a resolving power of $R > 6000$ is needed. If alternatively fluorinated calcium ions are delivered from ISOLDE, the removal of unwanted molecules is similar. The CaF molecules are expected to survive the cooling and bunching procedure in the buncher of ISOLTRAP as has been observed for fluorinated hafnium ions, HfF_3.

The mass measurements can be performed within about 4-5 shifts, in particular if the ISOLDE beam is already optimized for ^{38}Ca. The mass of the β-decay daughter nucleus is very well known (uncertainty of the mass excess is about 0.4 keV). In fact, $^{38}K^m$ is one of the nine precisely measured $0^+ \rightarrow 0^+$ transitions. Therefore, alternating measurements of ^{38}Ca and $^{38}K^m$ will allow to achieve the high precision aimed for.

4 Beam time request

The overall beam time request is as follows:

- 1 shift to optimise the ISOLDE setting
- 9 shifts to measure the half-life of ^{38}Ca with a precision of better than 0.1%
- 5 shifts to measure the masses of ^{38}Ca and of $^{38}K^m$ with a precision of better than 1 keV.

This yields a total beam time request of 15 shifts.

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