V_{ud} determination from light nuclide mirror transitions

M. Brodeur^{1a}, J. Kelly^a, J. Long^a, C. Nicoloff^a, B. Schultz^a

^a*University of Notre Dame, Department of Physics, Notre Dame, IN 46556, U.S.A.*

Abstract

Thanks to extensive experimental efforts that led to a precise determination of the various superallowed $0^+ \rightarrow 0^+$ pure Fermi transition experimental quantities, we now have a very precise value for V_{ud} that leads to a stringent test of the CKM matrix unitarity. Despite this achievement, measurements in other less precise systems remain relevant as conflicting results could uncover unknown systematic effects or even new physics. One such system is the superallowed mixed transition, which can help refine the same theoretical corrections used for pure Fermi transitions and hence improve the accuracy of V_{ud} . However, as a corrected $\mathcal{F}t$ -value determination from these systems requires the more challenging determination of the Fermi Gamow-Teller mixing ratio, only five transitions, spreading from ^{19}Ne to ^{37}K , are currently fully characterized. There are several ongoing efforts to determine the mixing ratios for medium-mass nuclei. Measuring transitions in lighter nuclei, such as ^{17}F , ^{15}O , ^{13}N and ^{11}C , poses new challenges as their longer half-lives, ranging from 1 to 22 minutes, conflict with the time constraints present at the large radioactive ion beam facilities where these nuclei are typically produced. We will present a proposed ion trapping experiment to measure these transitions at the University of Notre Dame where time constraints are less stringent.

Keywords:

Fundamental symmetry, Mirror transitions, Ion trapping, Radioactive ion beams

1. Introduction

Despite a lack of fundamental understanding of some of its parameters [1], the Standard Model (SM) of particle physics has been deceptively successful.

¹corresponding author: mbrodeur@nd.edu

Hence, there is currently a large ongoing experimental effort at the energy [2], intensity [3] and precision [4, 5] frontiers to test the limits of the SM. One precision test of the SM is related to the Cabibbo-Kobayashi-Maskawa (CKM) matrix, which relates the quark's eigenstates under the weak interaction with its regular eigenstates. Under the assumption that the standard model is complete, this mixing matrix should be unitary. Alternatively, non-unitarity could either be due to erroneous experimental quantities or indicate new physics beyond the SM. The most precise unitarity test [6] consists of summing the top row of the matrix: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2$. Among these values, V_{ud} , which relates the up and down quarks found in the nucleus, can be extracted from precision experiments measuring properties of β -decay. The most precise determination of V_{ud} comes from an ensemble of 14 corrected $\mathcal{F}t$ -values of superallowed $0^+ \rightarrow 0^+$ pure Fermi β -decays [6]:

$$|V_{ud}|^2 = \frac{K}{\overline{\mathcal{F}t}(1 + \Delta_R^V)G_F^2}, \quad (1)$$

where $K/(\hbar c)^6 = 8120.2776(9) \times 10^{-10} \text{ GeV}^{-4} \text{ s}$, $G_F/(\hbar c)^3 = 1.1663787(6) \times 10^{-5} \text{ GeV}^{-2}$, Δ_R^V is the transition-independent part of the radiative correction and $\overline{\mathcal{F}t}$ is the average of the 14 most precise $\mathcal{F}t$ values. Thanks to a large improvement in the quality of the experimental data [7], we now have a very precise value for $V_{ud} = 0.97417(21)$ leading to the most stringent unitarity test so far [6].

2. Motivation

Other than superallowed $0^+ \rightarrow 0^+$ pure Fermi β -decays, V_{ud} can be extracted from other decays mediated by the weak interaction: pion decay, neutron decay and superallowed mixed Fermi β -decays [8]. Even if measurements in these systems are less precise than pure Fermi decay, they remain important as conflicting results could uncover unknown systematic effects or even new physics. One of these, superallowed mixed transitions [8], can also help refine the same theoretical corrections used for pure Fermi decays, hence improving V_{ud} . However, extracting V_{ud} from mixed transitions requires knowledge of one more experimental quantity, the Fermi - Gamow-Teller mixing ratio ρ :

$$|V_{ud}|^2 = \frac{K}{\overline{\mathcal{F}t}(1 + \Delta_R^V)G_F^2[1 + (f_A/f_V)\rho^2]}, \quad (2)$$

Figure 1: Schematic of the proposed experimental setup for the measurements of $a_{\beta\nu}$ at the University of Notre Dame. The set up **will** be located at the Nuclear Science Laboratory where the RIB will be produced by transfer reactions of stable beams from a tandem interacting with a gas target. *TwinSol* will then separate the products before being stopped (see text). The setup will comprise a RFQ cooler and buncher, an MR-ToF for purification and a Paul trap where the measurement is performed.

where $f_{A,V}$ are the statistical rate functions of either the axial-vector or vector part of the interaction. This mixing ratio can be obtained from the measurement of one of the following three correlation coefficients [8]: the β asymmetry parameter A_β , the neutrino asymmetry parameter B_ν , or the β -neutrino angular correlation coefficient $a_{\beta\nu}$.

Because of the inherent difficulties in obtaining ρ , V_{ud} can only be extracted from 5 mirror transitions: ^{19}Ne , ^{21}Na , ^{29}P , ^{35}Ar , and ^{37}K [8]. However, there are currently several efforts to both measure ρ more precisely in some of these existing cases [9] as well as to measure ρ for new cases like ^{23}Mg [10]. On the other hand, besides a β asymmetry parameter measurement of ^{17}F [11] that showed to be very weakly sensitive to ρ [8], there have been very few efforts to measure correlation coefficients in light ($A < 19$) mirror transitions. This could be partly due to their more challenging long half-lives (up to 22 min.) that conflict with time constraints of large RIB facilities typically producing these nuclei. In the following, we propose to determine ρ for not only the *regular* medium mass nuclei but also the light nuclei ^{11}C , ^{13}N , ^{15}O , ^{17}F at the University of Notre Dame where time constraints are less stringent.

3. Proposed Program

The β -neutrino angular correlation parameter $a_{\beta\nu}$ could be measured at *TwinSol* facility [12] of the University of Notre Dame (see Fig. 1). Radioactive ion beams (RIB) are produced at *TwinSol* by transfer reactions of heavier projectiles on lighter gas targets. The stable projectiles are accelerated by

an up to 10 MV terminal voltage tandem. *TwinSol* separates most of the primary beam from the transfer reaction products while suppressing some of the unwanted reaction products from the desired ones. Furthermore, for RIB close to stability, such as mirror transitions, a proper projectile-target combination that leads to minimal contamination can be chosen. For instance, ^{17}F was recently produced from a $^{16}\text{O}(d,n)$ reaction with sole radioactive contaminant ^{15}O in a proportion of 8 parts per 10^4 . Furthermore, sufficient expected rates from 10^6 to 10^7 particles/s (e.g. 2×10^6 ^{17}F have been produced) for the species of interest can be produced.

The challenge of performing the measurements using the *TwinSol* beams lies in the need to decelerate (and thermalize) the ≈ 40 MeV RIB to energies amenable to an ion trap. Two possibilities are currently being investigated. **The first option is to reduce the energy of the radioactive ions with a solid material and then thermalize them in a gas cell**, a common procedure at in-flight facilities [14, 15, 16, 17, 18]. In the present case both the low energy of the beam and the light mass of the ions poses a challenge. The low energy requires finely adjusted thin degraders and thin gas cell windows to efficiently deliver the ions in the gas cell. The light mass of the ion will result in a large straggling of the beam requiring long stopping length or higher pressure. The above challenges can however be overcome and stopping and extraction efficiencies for light ions down to $A = 8$ of around 4% have previously been observed [19]. The second possibility would follow the Isotope Separation On-Line (ISOL) method [20], where the ions would stop in a solid that would be heated allowing the radioactive atoms to diffuse from the material into an Electron cyclotron resonance (ECR) ion source [21] that can then re-ionize the ions. The efficiency of this method is however strongly sensitive to the chemistry of the element in question. For example, at the GANIL ISOL facility, ^{15}O can be re-ionized with an efficiency of around 7.5%, while ^{13}N and ^{18}F presents much lower efficiencies of 0.3% and 0.03% respectively [22].

Following one of the front-ends described above, the experimental set-up (shown in Fig. 1) will comprise a radio-frequency quadrupole (RFQ) [23] that will serve the dual purpose of cooling the radioactive ions by collision with a buffer gas and bunching the continuous incoming beam. The bunches would then be sent to a multi-reflection time-of-flight spectrograph (MR-ToF) [24] that will separate contaminant ions of different mass by their time-of-flight. Downstream from the MR-ToF, a Bradbury-Nielsen gate [25] would block the contaminant bunches while letting the species of interest pass. The MR-ToF has been simulated [26], designed (based on [27]) and is currently being

assembled [28]. Finally, the pure bunches of ions will be sent and captured in a Paul trap where $a_{\beta\nu}$ will be inferred from the shape of the daughter nuclei's energy spectrum [29]. Because of the low kinetic energy of the recoil on the order to a few hundred eV, calorimetric techniques cannot be used to measure the energy of the recoil [30]. This energy is instead obtained indirectly by a time-of-flight (TOF) method. This method requires holding the radioactive nuclei in a well-define volume and measuring the difference in time taken to reach two different detectors between the positron and the daughter nuclei. There are two techniques for holding the cloud of radioactive nuclei in place. In the first technique, a magneto-optical trap (MOT) is used to hold neutral atom in place, as done for the measurement of $a_{\beta\nu}$ for ^{21}Na [31]. This technique suffers from low capture efficiency, requiring a large number of initial nuclei. A more efficient technique, consist of holding the radioactive nuclei in ionic form using a Paul trap as done by the LPCtrap group [29, 30]. The presence of a radio-frequency field, required to confine the ions in the ion trap, however affects the trajectory of the emitted recoil and need to be taken into account [29]. In the time-of-flight method, the start signal is produced by electron hitting a plastic scintillator detector, while the recoil nucleus hitting a micro-channel plate detector gives the stop signal. One of the main challenges in measuring $a_{\beta\nu}$ for $A < 19$ is the long half-life that may require storage time in the minute range. However, ion trapping lifetimes greater than 30 minutes have, been demonstrated for cluster experiments [32]. More extended lifetimes can be reached with appropriate buffer gas cooling. For instance, trapping lifetimes of over two hours where reached in a Paul trap for europium ions in a helium gas pressure of 5×10^{-6} mbar [33].

To have a comparable relative uncertainty to the other experimental quantities (lifetimes and Q -values) [34] an uncertainty of 0.5% for $a_{\beta\nu}$ will be targeted. The LPCTrap recently performed such a measurement on ^{35}Ar with an estimated uncertainty of 0.5% [30]. This measurement was done with about 2.5×10^4 trapped $^{35}\text{Ar}^+$ ions per bunch (the total number of ions, including contaminants, was space-charged limited to 1.5×10^5 ions) in the RFQ cooler and buncher. This can be translated to an average rate of 1.25×10^5 ions/s. In comparison, assuming a stopping efficiency of 4%, and the measured ^{17}F production rates of 2×10^6 ions/s at *TwinSol*, 0.8×10^5 ions/s are expected at the RFQ. These rates are comparable to the rates that led to a 0.5% relative uncertainty measurement using the LPCTrap.

4. Conclusion

The standard model can be challenged by precisely determining the unitarity of the CKM matrix. The leading term in the unitarity test, V_{ud} , can be accessed from precise β -decay measurements. While the most precise determination of V_{ud} currently comes from superallowed $0^+ \rightarrow 0^+$ pure Fermi β -decays, alternative ways of obtaining this matrix element are of importance as they could point to either new physics or experimental discrepancies. Superallowed mixed Fermi β -decays are of particular interest as they can be used to help refine and test the same theoretical corrections used in pure Fermi decays. Determination of V_{ud} from the mixed transitions however requires the determination of the mixing ratio ρ and this quantity is only known for five nuclei. We presented the plan to determine ρ from the precision measurement of the β -neutrino angular correlation coefficient $a_{\beta\nu}$ using a Paul trap at the University of Notre Dame. More specifically, we plan on measuring $a_{\beta\nu}$ for the more challenging light transitions: ^{11}C , ^{13}N , ^{15}O , ^{17}F , in which the long half-lives render the measurements difficult. The more flexible beam schedule at the University of Notre Dame gives a competitive advantage to perform that type of measurement and it will allow for the determination of V_{ud} for the lightest mirror transitions, where other interesting effects such as the possible presence of scalar current in the decay can be probed. However, several challenges related to the efficient stopping of the RIB from TwinSol and the long-term trapping of the RIB in the Paul trap will have to be overcome.

This work was supported in part by the US National Science Foundation Grant PHY-1419765.

- [1] N. Severijns, and O. Naviliat-Cuncic, [Annu. Rev. Nucl. Part. Sci. **61**, 23 \(2011\)](#)
- [2] J.D. Hobbs, M.S. Neubauer and S. Willenbrock, [Rev. Mod. Phys. **84**, 1477 \(2012\)](#)
- [3] J.L. Hewett *et al.*, [arXiv:1401.6077 \[hep-ex\]](#)
- [4] J.S.M. Ginges and V.V. Flambaum, [Phys. Rep. **397**, 63 \(2004\)](#)
- [5] N. Severijns, M. Beck and O. Naviliat-Cuncic, [Rev. Mod. Phys. **78**, 991 \(2006\)](#)

- [6] J.C. Hardy and I.S. Towner [Phys. Rev. C **91**, 025501\(2015\)](#)
- [7] J.C. Hardy and I.S. Towner, [J. Phys. G: Nucl. Part. Phys. **41**, 114004 \(2014\)](#)
- [8] O. Naviliat-Cuncic and N. Severijns, [Phys. Rev. Lett. **102**, 142302 \(2009\)](#)
- [9] N. Severijns, [J. Phys. G: Nucl. Part. Phys. **41** 114006 \(2014\)](#)
- [10] N. Severijns, G. Neyens and M. Bissell, [CERN-INTC-2013-013/INTC-O-017, Section 2.2.3 \(2013\)](#)
- [11] N. Severijns *et al.*, [Phys. Rev. Lett. **63**, 1050 \(1989\)](#)
- [12] F.D. Becchetti *et al.*, [Nucl. Instr. and Meth. Phys. Res. A **505**, 377-380 \(2003\)](#)
- [13] J. Äystö, [Nucl. Phys. A **693**, 477 \(2001\)](#)
- [14] D.J. Morrissey *et al.*, [Nucl. Instr. and Meth. B **266**, 4822 \(2008\)](#)
- [15] M. Wada *et al.*, [Nucl. Instrum. Methods B **204**, 570 \(2003\)](#)
- [16] G. Savard *et al.*, [Nucl. Instr. and Meth. in Phys. Res. B **204**, 582 \(2003\)](#)
- [17] S. Eliseev *et al.*, [Nucl. Instr. and Meth. in Phys. Res. B **266**, 4475 \(2008\)](#)
- [18] M. Ranjan *et al.*, [EPL **96**, 52001 \(2011\)](#)
- [19] A. Takamine *et al.*, [Rev. Sci. Instrum. **76**, 103503 \(2005\)](#)
- [20] P. Van Duppen, [Lect. Notes Phys. **700**, 37 \(2006\)](#)
- [21] R. Geller, Proc. 1st Int. Conf. Ion Sources, Saclay, p. 537 (1969).
- [22] S. Gibouin, *Contributions à l'étude de la production de faisceaux d'ions radioactifs par la méthode ISOL*, Ph.D. thesis, Université de Caen (2003)
- [23] F. Herfurth *et al.*, [Nucl. Instr. and Meth. A **469**, 254 \(2001\)](#)
- [24] H. Wollnik and M. Przewloka, [Int. J. Mass Spectrom. Ion. Processes **96**, 267 \(1990\)](#)

- [25] T. Brunner *et al.*, [Int. J. Mass Spectrom.](#) **309**, 97 (2012)
- [26] J. Kelly *et al.*, Nucl. Instr. and Meth. B (this issue)
- [27] R. Wolf *et al.*, [Nucl. Instr. and Meth. A](#) **686**, **82** (2012)
- [28] B. Schultz *et al.*, Nucl. Instr. and Meth. B (this issue)
- [29] G. Ban *et al.*, [Ann. Phys. \(Berlin\)](#) **525**, **576** (2013)
- [30] X. Fabian *et al.*, [EPJ Web of Conf.](#) **66**, 08002 (2014)
- [31] P.A. Vetter *et al.*, [Phys. Rev. C](#) **77**, 035502 (2008)
- [32] J.H. Parks, S. Pollack and W. Hill, [J. Chem. Phys.](#) **101**, 6666 (1994)
- [33] S. Bhattacharyya *et al.*, [Pramana J. of Phys.](#) **67**, 1087 (2006)
- [34] N. Severijns *et al.*, [Phys. Rev. C](#) **78**, 055501 (2008)

Figure