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# Precision measurements in nuclear beta decay

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**Abstract** Precision measurements in nuclear beta decay provide sensitive means to determine the fundamental coupling of charged fermions to weak bosons and to test discrete symmetries in the weak interaction. The main motivation of such measurements is to find deviations from Standard Model predictions as possible indications of new physics. I focus here on two topics related to precision measurements in beta decay, namely: i) the determination of the $V_{ud}$ element of the Cabibbo-Kobayashi-Maskawa quark mixing matrix from nuclear mirror transitions and ii) selected measurements of time reversal violating correlations in nuclear and neutron decays. These topics complement those presented in other contributions to this conference [1, 2].

**Keywords** Tests of fundamental symmetries · Precision measurements in nuclear beta decay and neutron decay.

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## 1 Introduction

The role of precision measurements in nuclear and neutron decays [3–6] has recently been revisited from a theoretical perspective [7] considering current and future results from the LHC. It appears that experiments at low energies currently provide the most stringent constraints on exotic scalar and tensor interactions that are not accessible so far to experiments at high energy colliders. This illustrates the complementarity of precision measurements at low energies relative to those at high energy and motivates further improvements in the level of sensitivity of precision measurements at low energies. Future prospects to reach a precision level of $10^{-4}$ in the measurements of correlation

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parameters in beta decay make these observables very attractive as probes to reach the TeV scale [7].

This contribution describes recent results and new plans for precision measurements in nuclear and neutron decays concerning two topics in the field: the first is the determination of the $V_{ud}$ element of the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix from nuclear mirror transitions and the second is the search for time reversal violating correlations in nuclear and neutron decays. The selection of topics is such as to complement those covered by other contributions to this conference [1,2].

## 2 The $V_{ud}$ element from nuclear mirror transitions

It has recently been pointed out [8] that super-allowed transitions within isospin doublets (termed "mirror transitions") provide an independent source for the determination of the $V_{ud}$ element of the CKM matrix, in addition to pure Fermi transitions, neutron decay and pion beta decay. The evaluation of $V_{ud}$ from the four known semi-leptonic decays has recently been analyzed in detail [9] along with the determination of the other two elements of the first row in the CKM matrix.

Like for super-allowed pure Fermi transitions, mirror transitions require the inclusion of small nuclear structure and isospin symmetry breaking corrections for the determination of the corresponding $\mathcal{F}t$-values [8] and like neutron decay, they require in addition the measurement of a correlation coefficient since the beta decay involves both, the Vector and Axial-vector interactions.

For a transition within an isospin doublet, the master formula to extract the value of $V_{ud}$ is [8]

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

where $K/(\hbar c)^6 = 2\pi^3 \ \ln 2\, \hbar/(m_e c^2)^5$ and has the value $K/(\hbar c)^6 = 8120.278(4) \times 10^{-10}$ GeV$^{-4}$s, $G_F/(\hbar c)^3 = 1.16637(1) \times 10^{-5}$ GeV$^{-2}$ is the Fermi constant, $\mathcal{F}t$ is the corrected absolute decay rate, $f_A/f_V$ is the the ratio between the statistical rate functions for the axial and the vector interactions, $\rho$ is the Gamow-Teller to Fermi (GT/F) mixing ratio, and $\Delta_R^V$ is a transition-independent radiative correction. The experimental quantities that enter the determination of $\mathcal{F}t$ in Eq.(1) are identical to those in pure Fermi transitions [9]. The dominant contribution to the error on $V_{ud}$ arises here from the experimental uncertainties in the GT/F mixing ratio, $\rho$. Significant improvements have been made recently in the measurements of relevant quantities and this is illustrated here below.

### 2.1 Measurements of spectroscopic quantities

The spectroscopic quantities entering the determination of $\mathcal{F}t$ are the half-lives, branching ratios and $Q_{\rm EC}$ values of the mirror transitions. An nice illustration of recent improvements is provided by precision measurements of the $^{19}$Ne half-life. Figure 1 shows the values of the half-life adopted in the survey of Ref.[10] (left panel) as a function of the year of publication. The zoom for year 2012 shows three recent results from measurements carried out at KVI [11], at TRIUMF [12] and at GANIL [13] with relative precisions smaller than $5 \times 10^{-4}$. It is to be noted that the technique used at GANIL offers additional opportunities for further improvements.

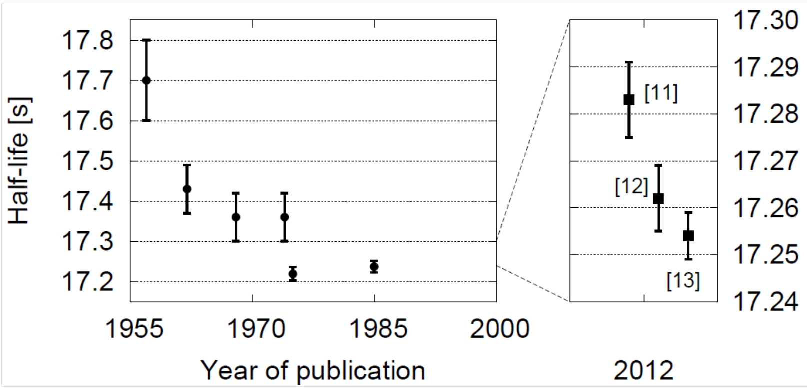


**Fig. 1** Values of the $^{19}$Ne half-life versus the year of publication. The zoom for year 2012 indicates the three new values with the corresponding references.

Lifetime measurements have also been carried out in the decay of $^{29}$P, $^{31}$S and $^{39}$Ca at Jyväskylä [14] but the results have not yet been released. Mass measurement have recently been performed on $^{31}$S with the Penning trap JYFLTRAP [15] and it would be extremely useful to improve previous mass results obtained from reaction experiments by using Penning trap mass spectrometry.

## 2.2 Measurements of correlations

Measurements of correlations between the kinematic vectors involved in the beta decay of $T = 1/2$ mirror transitions enable to determine the GT/F mixing ratio, $\rho$. Until recently [3] precision measurements of $\beta\nu$ angular correlations have been motivated by searches for exotic scalar and tensor couplings. Measurements in mirror decays of $^{21}$Na and $^{37}$K have been used within the SM to extract the GT/F mixing ratio [8].

During the week of the symposium, the LPC-Caen group was incidentally carrying out a measurement of the $\beta\nu$ angular correlation in the decay of $^{35}$Ar at GANIL [16]. The setup is based on a Paul trap surrounded by detectors. The current version is shown in Fig. 2 and has been described in detail elsewhere for the measurement of the shake-off probability following $^{6}$He$^{+}$ decay [17]. The setup enables the separation of the different charge states of Cl ions following the beta decay of $^{35}$Ar in the Paul trap.

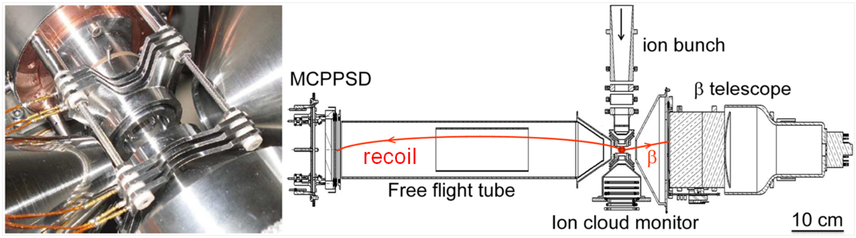


**Fig. 2** The LPCTrap at GANIL used for the measurement of the $\beta\nu$ correlation in $^{35}$Ar decay. Left panel: picture of the Paul trap made out of rings. Right panel: scheme of the setup with the electron telescope and the ion detectors around the Paul trap.

The LPC-Caen group has collected data corresponding to a statistical precision of about 0.4-0.5% [16] on the angular correlation coefficient $a$. Although this will not improve current constraints on exotic scalar couplings [3], it will provide a competitive value for the GT/F mixing ratio in this decay. In the near future, the group considers also a measurement of the $\beta\nu$ angular correlation in $^{19}$Ne decay with the same setup.

Experiments with polarized nuclei can access the beta asymmetry parameter, $A$. For several decays from mirror nuclei, the mixed transition between the ground states of the parent and daughter nuclei is accompanied by a pure GT transition to an excited state in the daughter nucleus, with a branching ratio of few % (ex. $^{21}$Na, $^{23}$Mg, $^{29}$P, $^{35}$Ar, $^{37}$K). Some of these nuclei can be easily polarized by optical pumping and be implanted in suitable targets. The measurement of the beta asymmetry of beta particles detected in coincidence with the de-exciting gamma ray provides a measurement of the initial nuclear polarization. Such measurements of the beta decay asymmetry will become feasible at the new BECOLA (BEam COoler and LAser) low energy line at NSCL [18] and can provide improved determinations of the GT/F mixing.

## 3 Searches for time reversal violation

Phenomenologically, effects of time reversal invariance violation in beta decay manifest themselves by the presence of complex phases between the possible couplings (scalar $S$, vector $V$, axial vector $A$ and tensor $T$) [19].

The motivation for the measurements of T-violating correlations is connected with searches for new sources of CP-violation. In semi-leptonic decays involving the lightest quarks, the effects due to the standard electroweak CP-violating phase are strongly suppressed, since these arise at higher order because all three quark families have to be involved.

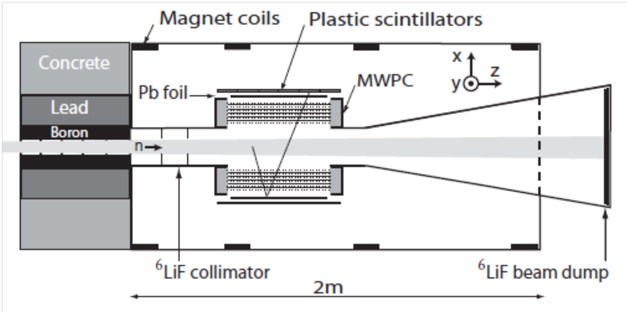


**Fig. 3** Schematic view of the experimental setup for the measurements of the $R$ and $N$ coefficients in neutron decay. From Ref. [20].

In nuclear beta decay, searches for T-violation have traditionally been performed by measuring two triple correlations [3], one driven by the $D$ coefficient and the other driven by the $R$ coefficient [19]. Since the first is P-even and the second is P-odd, the two correlations do not probe the same physics. The $D$ coefficient is generally considered as sensitive to an imaginary phase between the standard $V$ and $A$ couplings whereas the $R$ coefficient is sensitive to a phase between an exotic, $S$ or $T$, coupling and a standard one, $V$ or $A$.

## 3.1 Triple correlations involving spin

The status of the most recent measurement of the $D$ coefficient in neutron decay has been presented in another contribution to this symposium [2].

In contrast, the $R$ coefficient had until recently never been measured in neutron decay. The measurement has been carried out at the cold neutron facility FUNSPIN of the spallation source SINQ at the Paul Scherrer Institute. Polarized cold neutrons decay in a volume surrounded by two rectangular multi-wire proportional chambers (MWPC), followed by hodoscopes made of plastic scintillators (Fig. 3). Electrons from neutron decay are first tracked by the MWPC. A fraction of about $10^{-3}$ backscatter from Pb foils, placed between the MWPC and the hodoscopes, and are also tracked by the MWPC. The trigger for such events is given by the hodoscope located at the opposite side of the beam line. Mott polarimetry is applied to analyze the electron polarization from the asymmetry of backscattered events.

A remarkable feature of this experiment is that, in addition to the measurement of $R$, the tracking capabilities of the apparatus enable a simultaneous determination of the time reversal invariant $N$ coefficient [19]. This coefficient drives the correlation between the neutron polarization and the electron spin, and it is different from zero in the SM. The determination of $N$ offers a sensitive check of the proper operation of the polarimeter through a control of the analyzing power. The final results of this experiment [20] lead to $R_n = 0.004 \pm 0.012 \pm 0.005$, consistent with zero, and to $N_n = 0.067 \pm 0.011 \pm 0.004$

consistent with the SM prediction under the conditions of the experiment, $N_{\rm SM} = 0.068$. These results improve the constraints between the phases of the Scalar couplings relative to the Vector and the Tensor couplings relative to the Axial-vector. It has been pointed out [21] that the constraints on T-violating interactions obtained from searches of atomic and molecular electric dipole moments (EDMs), are considerable more stringent than the direct limits obtained from the measurement of the $R$ coefficient in neutron decay. It has however also been noticed there that the theoretical uncertainties in the analysis of EDM results could be large, so that the direct limits on new interactions are useful.

In the beta decay of nuclei, the most stringent limit on a phase between a Tensor and the Axial-vector couplings has been obtained in the decay of $^8$Li [22], in a measurement of the $R$ correlation coefficient. The experiment used polarized nuclei produced by a polarization transfer reaction induced by an initially polarized beam, and the transverse polarization of electrons was analyzed by Mott polarimetry. A new experiment, also in $^8$Li decay, has been setup at TRIUMF [23] to improve the precision obtained previously. The experiment uses a low energy optically polarized $^8$Li beam and Mott polarimetry for the analysis of the electron transverse polarization. This group expects to reach a sensitivity that probes the SM final state interactions which are at the level of $R_{\rm FSI} = 7 \times 10^{-4}$.

### 3.2 Triple correlations not involving spin

It has recently been pointed out [24], that a triple linear momentum correlation –that is a correlation not involving spin vectors– would be potentially sensitive to other sources of CP-violation that the $D$ and $R$ coefficients considered so far. The SM expected value for the T-odd asymmetry associated with such a correlation is strongly suppressed, leaving a large room to search for non standard sources of CP-violation.

From an experimental perspective, the triple momentum correlation involves the detection of low energy photons from the radiative decay mode. This poses severe requirements for a clean and sensitive measurement. Interesting decays from nuclei should then fulfill a number of conditions in order the signal can be clearly separated from background induced by other photons. Some of the conditions are: i) The decay should proceed via a $\beta^-$ decay in order to avoid the presence of 511 keV photons that would result from the $\beta^+$ annihilation in detectors and surrounding materials; ii) The transition should proceed from the ground state of the parent to the ground state of the daughter in order also to avoid subsequent $\gamma$ background; iii) The detection of the recoiling ions after beta decay requires that the decaying system be stored in a trap or that their decay occurs in flight in a low energy beam.

These conditions exclude most of the super-allowed mirror transitions within isospin doublets [10] which proceed by $\beta^+$ decay except for the neutron and tritium decays. An interesting allowed transition which fulfills all conditions above is the one from $^6$He. The shake-off probability of the singly bound electron in the final state, which is of the order of 2%, has recently been measured [17] what demonstrated that probing small branchings with in-trap decay spectroscopy is possible with the LPC-Trap. The measurement of the radiative decay mode, $^6\mathrm{He}^+ \rightarrow ^6\mathrm{Li}^{2+} + e^- + \bar{\nu}_e + \gamma$, appears to be feasible by adding suitable photon detectors around the Paul trap.

It has been explicitly shown (Appendix B of Ref.[24]) that the T-violating contribution to the radiative neutron decay rate is proportional to $(1 - \lambda^2)$ where $\lambda = g_A/g_V$ is the ratio between the Axial-vector and Vector couplings. The corresponding asymmetry goes like $(1-\lambda^2)/(1+3\lambda^2)$ which is the expression of the $\beta\nu$ angular correlation coefficient, $a$, in the SM. In order to provide a crude comparison between different nuclear decays, it is useful to make the substitution $\lambda \rightarrow \rho/\sqrt{3}$, where $\rho$ is the GT/F mixing ratio introduced in Sec.2. For pure Fermi transitions $\rho = 0$ and $a_F = 1$, and for pure GT transitions $\rho \rightarrow \infty$ and $a_{GT} = -1/3$. The SM values for $\rho$ and $a$ in mirror decays can be found in Ref.[10]. Depending on the goal, one may either look at candidates with small or with large values of $a$. If the purpose is to test the SM prediction for the asymmetry of the triple momentum term, then interesting candidates should have a large value of $a$, like $^{35}$Ar. If, in contrast, the goal were to look for new mechanisms of T-violation, candidates with small values of $a$ are expected to be more attractive, like $^{19}$Ne. These two examples are however problematic from the experimental point of view, since they are both $\beta^+$ decays. The only mirror transitions which proceed by a $\beta^-$ decay (the neutron and tritium) have both rather small values for $a$. The prospects for a measurement of the asymmetry in these decays looks rather challenging with presently available beams and sources.

### 3.3 Outlook

The examples given in Sec.2 illustrate that precision measurements in mirror transitions will be able to improve the determination of $V_{ud}$ in nuclei. In particular, the fast progress in high precision lifetime measurements, like $^{19}$Ne, is quite remarkable, and progress in other decays will soon be made as well.

Further progress with the the determination of $V_{ud}$ from mirror transitions also require input from theory for both, the determination of the $f_A/f_V$ ratio, Eq.(1), with a smaller uncertainty as well as to carefully account for the nuclear structure corrections necessary in the determination of the $\mathcal{F}t$-values [10].

There is currently a single experiment, conducted by the Rykkyo group at TRIUMF, using beta decay in nuclei for testing time reversal invariance in the decay of polarized $^8$Li. The experiment has collected data and expects to reach a sensitivity level corresponding to final state effects.

Prospects for a measurement of the radiative decay mode probability with trapped $^6$He are being considered which may constitute a first step toward a measurement of a triple momentum correlation asymmetry in a suitable decay.

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