EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

# Q-values of Mirror Transitions for fundamental interaction studies

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**Abstract**

The ft values for the $0^+ \rightarrow 0^+$ superallowed β transitions currently provide the best test of the CVC hypothesis, and the most precise determination of the $V_{ud}$ element of the CKM matrix. Recent experimental advances, including direct mass measurements with Penning traps, have led to the precision in the corrected *Ft* values being dominated by the theoretical corrections rather than experiment. An alternative route are the isospin $T$=1/2 mirror transitions where experimental uncertainties dominate over the theoretical inputs and which can provide an independent test of CVC, and ultimately an independent evaluation of $V_{ud}$. We propose mass measurements of 4 different mirror transitions aiming for a precision of better than 100eV on the *Q*-value.

**Requested shifts**: 20 shifts, (split into 2 runs)
**Beamline:** Central beamline until ISOLTRAP

## 1. Introduction

In recent years several new tests of the Standard Model (SM) have been performed in the field of low energy weak interaction physics [Sev2011]. At ISOLDE, a measurement of the β asymmetry coefficient *A* for the isotope $^{67}$Cu [Wau2010] was done with the Low Temperature Nuclear Orientation setup NICOLE, while the WITCH spectrometer [Bec2011] is steadily progressing towards a goal of a high-precision measurement of the $\beta-\nu$ angular correlation coefficient $a$ in $^{35}Ar$.

Another field of fundamental interaction studies pursued at ISOLDE is the test of the unitarity of the CKM quark mixing matrix and of the Conserved Vector Current (CVC) hypothesis using the $0^+ \rightarrow 0^+$ superallowed $\beta$ transitions. The measurements that contribute to the superallowed ft values are the half-lives, branching ratios, and $\beta$-decay $Q$-values. The masses of $^{38}Ca$ and $^{26m}Al$ [Geo2008], $^{22}Mg$ [Muk2004], $^{34}Ar$ [Her2002], and $^{74}Rb$ [Kel2004] have all been measured with the ISOLTRAP facility at ISOLDE, and these mass measurements have contributed to the most precise test of the CVC hypothesis to date [Har2009].

The advent of the next generation of radioactive ion beam facilities such as ISOLDE, and improved experimental techniques such as direct $Q$-value determinations via Penning trap mass measurements, have led to the precision in the corrected superallowed $Ft$ values being limited by the theoretical corrections, rather than experimental inputs [Tow2010]. While direct tests of these theoretical corrections are being pursued, an alternative is to make further measurements in other systems, such as free neutron decay [Abe2008] or beta decay between isospin $T$=1/2 mirror nuclei [Nav2009], where the corrected $Ft$ values are still dominated by experimental, rather than theoretical, inputs.

In the following we propose to improve the precision in the mirror $\beta$-decay $Ft$ values via direct mass measurements of both the mother and daughter nuclei using the ISOLTRAP mass spectrometer. Combined with $Ft$ from the superallowed decays, improvement in the mirror $ft$ values leads to an improved precision in the Standard Model value for the Fermi/Gamow-Teller mixing ratio $\rho$, which can be used to test the standard model by comparing with the experimental values for $\rho$ extracted from correlation measurements [Sev2011, Sev2013]. Alternatively, combining the experimentally determined values for $\rho$ with their respective mirror $ft$ values can contribute to the CKM matrix unitarity test, and thus constrain physics beyond the standard model by determining an independent value of $V_{ud}$ [Nav2009].

## 2. Test of CKM unitarity using superallowed mixed mirror transitions

The corrected $Ft$ values for mirror transitions can be obtained from an evaluation similar to the one for the $0^+ \rightarrow 0^+$ superallowed transitions and which contains the $V_{ud}$ element of the CKM matrix [Sev2008]:

$$Ft_0^{mir} = f_V t^{mir}\left(1+\delta_{NS}^V+\delta_C^V\right)(1+\delta'_R)\left(1+\frac{f_A}{f_V}\rho^2\right) = \frac{K}{G_F^2 V_{ud}^2 C_V^2 (1+\Delta_R^V)}.$$

Here $f_V$ is the statistical rate function which depends on the Q-value of the decay, and $t^{mir}$ is the partial half-life of the transition which contains the branching ratio. The parameters $\delta'_R$ and $\delta_{NS}^V$ denote transition-dependent radiative corrections, where the former is calculated from quantum electrodynamics and the latter depends on nuclear structure. The isospin symmetry-breaking correction is depicted by $\delta_C^V$ and $K$ is a constant with the value $K$ = 8120.2776(9) × $10^{-10}$ GeV$^{-4}$ s [Ber2012]. $G_F$ is the Fermi coupling constant deduced from muon decay, $G_F/(\hbar c)^3$ = 1.16637(1) × $10^{-5}$ GeV$^{-2}$ [Ber2012]. $C_V$ = 1 is the vector coupling constant and $\Delta_R^V$ is a nucleus-independent radiative correction [Mar2006]. Due to the mixed Fermi/Gamow-Teller character of the mirror transition one more experimental value is required, however, compared to the $0^+ \rightarrow 0^+$ transitions, i.e. the Fermi/Gamow-Teller mixing-ratio $\rho$. This can be obtained from correlation measurements [Sev2008, Nav2009].

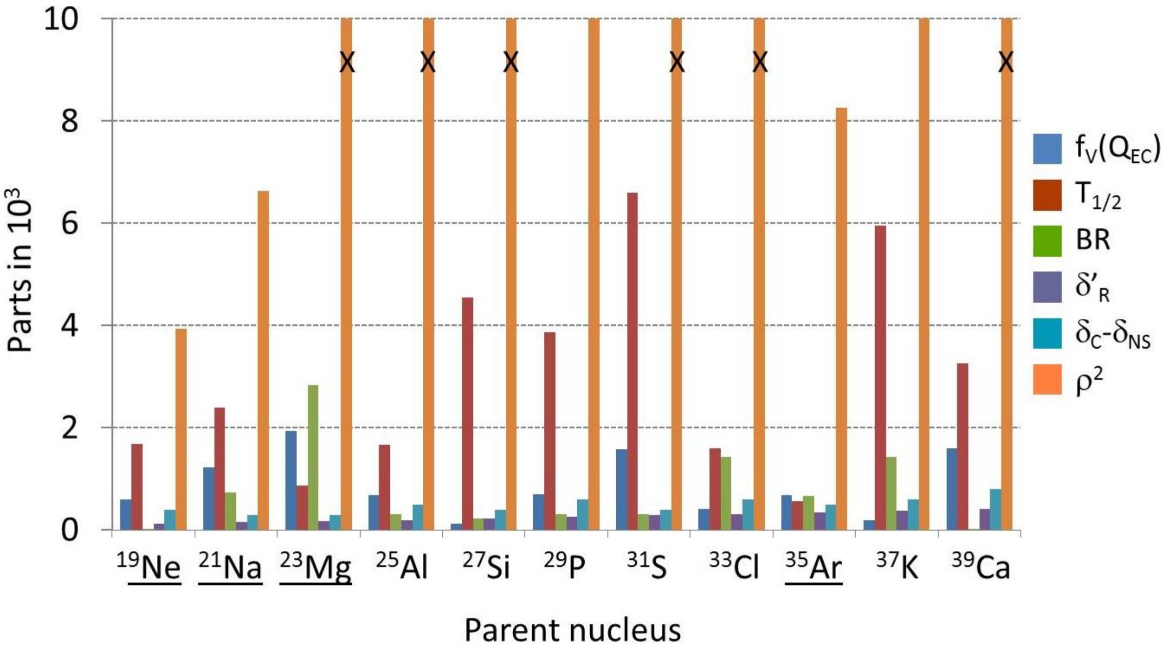


Fig.1: Contribution to the uncertainties in the mirror ft values from the measurements and theoretical corrections (taken from [Sev2011]). The left-most blue bars show the contribution from the β decay Q-value. The "x" indicates contributions larger than this scale.

Figure 1 shows the error budged as compiled in [Sev2011], which is mainly dominated by ρ. There is currently great interest in improving the knowledge of the mirror transitions for fundamental weak interaction studies, as evidenced by the number of projects where different observables are under investigation, such as:

- $^{35}$Ar → $^{35}$Cl: New physics (i.e. a fundamental scalar weak interaction component) is currently being searched for with the WITCH [Bec2011] and LPCTrap [Fle2011] experiments, both measuring the β−ν angular correlation coefficient *a* The limits on new physics from these depend on the experimental *ft* value as input, and would thus improve if the precision of the *Ft*-value can be increased. At present the *Ft*-value contributes a systematic error of 0.3% to the SM value of *a*.

  In addition it was shown recently [Nav2009b] that a measurement of the β asymmetry parameter, *A*, for $^{35}$Ar to a relative precision of 0.5% would yield a value for $V_{ud}$ that is only 3 times less precise than the value obtained from the entire dataset for the $0^+ \rightarrow 0^+$ superallowed β transitions [Har2009]. It was further pointed out [Sev2013] that if the precision of the *Ft*-value for $^{35}$Ar is improved by a factor of 5 a factor of almost 2 is gained in the precision of $V_{ud}$.

- $^{23}$Mg → $^{23}$Na: For this transition correlation measurements are planned at MSU [Nav2013]. Following ρ, the next largest uncertainties in the *ft* value are the branching ratio and the *Q*-value.

- $^{21}$Na → $^{21}$Ne: Here precise correlation data exist already for *a* [Vet2008] and better precision in the *Ft*-value would thus improve the limits for new physics from this case. In addition further new experiments with $^{21}$Na are planned for the so-called polarization-asymmetry correlation at MSU [Nav2011] and for the D-coefficient at KVI [Wil2010]. A proposal for a high-precision half-life measurement to improve the *ft* value for $^{21}$Na has also recently been accepted at TRIUMF [Fin2012a].

- $^{19}$Ne → $^{19}$F: This mirror β transition is of special interest as the measured asymmetry parameter [Cal1976] in combination with the *Ft*-value provides a very sensitive test of parity violation, i.e. to search for right handed weak currents (see e.g. Fig.4 in [Sev2011]). This sensitivity to right-handed weak currents, and thus to the mass of the $W_R$ boson, depends crucially on the *Ft*-value [Nav1991] such that a precise and accurate value is essential. Two new values of the $^{19}$Ne half-life have recently been published [Tri2012,Uji2013].

Determining the Q-value with a precision of a few 10 eV, a realistic proposition with a new measurement method [Eli2013], will reduce the contribution to the error budget to the point of being negligible. For the other pairs of nuclei than the suggested ones it is more challenging to produce sufficiently pure ensembles to be measured at ISOLTRAP or to produce both the mother and daughter from the same target ion source combination. Therefore we limit ourselves for the moment to these four cases.

## 3. Experimental procedure and required improvements

The ISOLTRAP experiment [Muk2008] has been running routinely for more than 20 years. Today it consists out of four ion traps (shown in Fig.2) to accumulate, purify, cool and measure an ion ensemble. The classical measurement cycle is finished by the Time-of-Flight Ion-Cyclotron-Resonance (ToF ICR) measurement to determine the sum of the two radial eigenfrequencies, equal in the ideal Penning trap to the cyclotron frequency.

Similar to the recently published offline measurements on the masses of $^{110}$Cd and $^{110}$Pd with a Ramsey type excitation, a statistical uncertainty for each single frequency can be obtained which yields a statistical uncertainty in the frequency ratio of $2*10^{-9}$, leading to an uncertainty in the mass of 1 keV [Fin2012b]. For the measurements suggested here the masses are less than one third of mass 110 *u*. Thus, the absolute uncertainty in the $Q_{EC}$-value can be reduced to at least 300 eV with the same type of measurement without any further technical improvements.

Detailed investigations of the ISOLTRAP set-up using carbon clusters over a wide range of masses showed a mass-dependent uncertainty correlated with the mass difference of the reference ion and the ion of interest of $10^{-11}$ per mass unit *u* [Kel2003]. This effect is negligible for the current proposal since the mass difference (or $Q_{EC}$) is small as compared to *u*. The residual systematic uncertainty can be reduced to essentially zero by applying the exact same conditions for the mother and the daughter isotopes such that it cancels out and the remaining uncertainty is purely statistical as was demonstrated for SHIPTRAP [Eli2011].

Important for this measurement at ISOLTRAP is the production of both ions of interest within the same target and ion-source unit. Nevertheless, the possibility of removing the other mass as well as additional contaminants to have a pure ion ensemble in the traps is required to achieve the precision of a few 10 eV on the $Q_{EC}$-value (see Tab.1). This will require suppression mechanisms for the stable ions, as the radioactive ions can be reduced by switching the proton beam off.

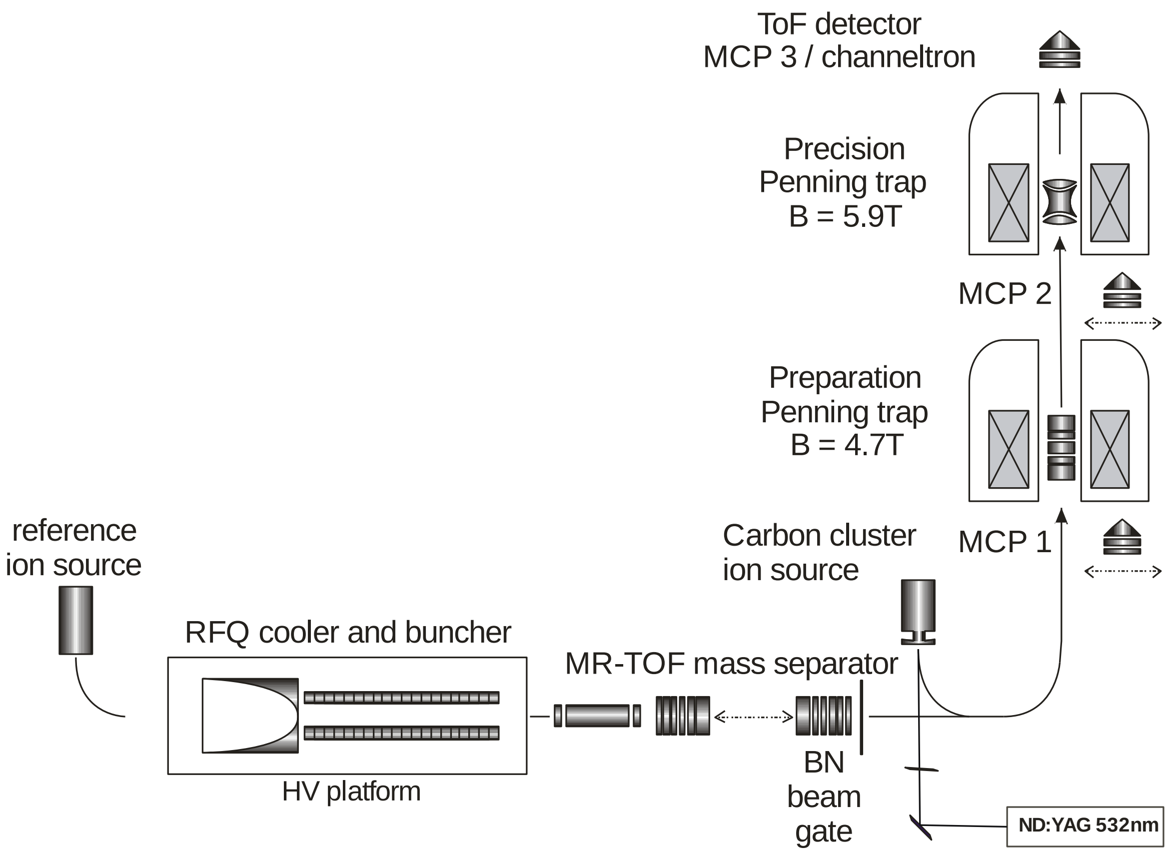


Fig. 2: Schematic overview of the ISOLTRAP set-up at the ISOLDE/CERN facility.

The conventional ToF-ICR method is currently limited in terms of the precision that it can achieve, even when using Ramsey fringes to drive the excitation [Geo2007a,b]. However, using a new technique [Eli2013], which includes the installation of a position sensitive detector for phase detection of the eigenmotion would lead to a relative statistical uncertainty at least down to $10^{-9}$ (at least twice better than currently achievable). This technique derives the cyclotron frequency in the same way as in the ToF-ICR method, but the two radial eigenfrequencies are measured in two independent measurements instead of via a resonant conversion between them. The higher precision is due to the measurement of the phase, which is collected for a certain waiting time. The limit of precision is determined by the stability of the voltage sources for the trap electrodes. New modules are under development and aim for stability allowing for relative precision down to $10^{-10}$. The currently achievable uncertainty in the $Q$-value is shown in Tab. 1, assuming the current estimated limit in relative precision for the cyclotron frequency.

Note additional cases for higher-mass mirror transitions are under investigation at JYFL [Kan2013]. Not yet foreseen, but possible in future are measurements of the same transitions at ISOLTRAP and at JYFLTRAP, which would provide an important test of the limit on reachable precision stemming from systematic uncertainties. This is desired as we are approaching relative uncertainties of $10^{-10}$ in frequency determination.

Tab. 1: *Q*-value and uncertainties of the mass excess (ME) values of the transitions shown in Fig.1 as published in the AME2012 [Aud2012]. Last column shows the achievable uncertainty using PI-ICR. The nuclei proposed for measurement are underlined.

| Mother nucleus | *Q*-value /keV | Mother Uncertainty ME/eV | Daughter Uncertainty ME/eV | Combined Uncertainty ME/eV | Anticipated uncertainty of the Q-Value assuming $10^{-9}$ /eV |
|---|---|---|---|---|---|
| <u>$^{19}$Ne</u> | 3239.50 | 160 | 0.86 | 160 | 18 |
| <u>$^{21}$Na</u> | 3547.14 | 276 | 38 | 279 | 28 |
| <u>$^{23}$Mg</u> | 4056.6 | 687 | 1.81 | 687 | 21 |
| $^{25}$Al | 4276.6 | 473 | 47 | 475 | 33 |
| $^{27}$Si | 4812.36 | 142 | 104 | 176 | 36 |
| $^{29}$P | 4942.6 | 563 | 0.49 | 563 | 27 |
| $^{31}$S | 5398.02 | 229 | 0.65 | 229 | 29 |
| $^{33}$Cl | 5582.5 | 391 | 1.35 | 391 | 31 |
| <u>$^{35}$Ar</u> | 5966.1 | 746 | 35 | 747 | 46 |
| $^{37}$K | 6147.45 | 94 | 207 | 227 | 49 |
| $^{39}$Ca | 6524.5 | 596 | 4.58 | 596 | 37 |

Finally the charge exchange half-live for Ar, Ne and F ions in the lower trap is on the order of 1s. This can be improved by installing a buffer gas cross piece containing a NEG pump as implemented in the WITCH system [Tan2011]. Furthermore for the long shutdown a bake out is planned to reduce the outgasing rate in the traps.

## 4. Target Ion-Source Combinations and ISCOOL

Using SiC or CaO target material will provide sufficient yield for the radioactive mother nuclei. The daughter ions are usually produced as a contamination. The contamination to ion-of-interest ratio should be small enough that it is possible to separate them in the MR-TOF separator (1:1000). The mother ions can be suppressed by switching off the protons, while the daughter ions are available as contamination or are added via the system of the mass markers. As an ion source we prefer a plasma ion source for its versatility. In case of the halogen/noble gas measurements, it would be best to have a cold transfer line, and thus we request a VD7 ion source. For the alkali and earth alkali pairs we prefer a hot transfer line (VD5).

In order to improve the knowledge of the path of the ions we would like to request the use of ISCOOL (and thus HRS) which, after the newest modification, should greatly improve the emittance of the plasma source [Bab2013]. While we note that the transmission of the ions may be reduced in this configuration, the efficiency should not drop below 60%, as shown by recent experiments with $^{23}$Mg using the HRS and ISCOOL at the end of 2012. Since we are working with near-stable and stable nuclei with high production cross sections, and we typically require only 1000 ions per pulse at ISOLTRAP, the reduction in efficiency due to HRS/ISCOOL will not be a limiting factor for this measurement.

### 5. Summary of requested shifts:

In [Fin2012b] it is shown that about 20 hours or 3 shifts are required for obtaining a relative statistical uncertainty of $10^{-9}$. We thus request 4 shifts (3 for measurement plus 1 as contingencies e.g. for understanding systematic effects) per measurement, as well as 2 additional shifts to prepare the transport between ISOLDE and ISOLTRAP, to find the optimal conditions for MR-TOF, and to make additional checks to understand/minimize the systematic uncertainties associated with the injection into the measurement trap, which will be essential in order to achieve a final uncertainty below 100eV in the Q-value [Eli2011, Rou2013].

Tab. 2: Beam time request.

| Run | Beam | Min. intensity | Target material | Ion source | Preparation | Shifts |
|---|---|---|---|---|---|---|
| 1 | $^{35}Ar/^{35}Cl$<br>$^{19}Ne/^{19}F$ | $1 \times 10^4$/s | CaO | VD7 | 2 | 4<br>4 |
| 2 | $^{23}Mg/^{23}Na$<br>$^{21}Na/^{21}Ne$ | $1 \times 10^4$/s | SiC | VD5 | 2 | 4<br>4 |

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# Appendix

## DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: *ISOLTRAP*

| Part of the Choose an item. | Availability | Design and manufacturing |
|---|---|---|
| ISOLTRAP | ☒ Existing | ☒ To be used without any modification |
| | | |
| [insert lines if needed] | | |

## HAZARDS GENERATED BY THE EXPERIMENT

Hazards named in the document relevant for the fixed ISOLTRAP installation.