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# PRECISION MASS MEASUREMENT OF ARGON ISOTOPES

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## Abstract

A precision mass measurement of the neutron-deficient isotopes $^{32,33,34}$Ar is proposed. Mass values of these isotopes are of importance for: a) a stringent test of the Isobaric-Multiplet-Mass-Equation, b) a verification of the correctness of calculated charge-dependent corrections as used in super-allowed β decay studies aiming at a test of the CVC hypothesis, and c) the determination of the kinematics in electron-neutrino correlation experiments searching for scalar currents in weak interaction. The measurements will be carried out with the ISOLTRAP Penning trap mass spectrometer.

# 1. Introduction

It is proposed to determine the masses of $^{32}$Ar, $^{33}$Ar, and $^{34}$Ar with the ISOLTRAP Penning trap mass spectrometer. The motivation for these measurements is manifold. The isotopes $^{32,33}$Ar can provide a stringent test of the Isobaric-Multiplet-Mass-Equation. $^{34}$Ar allows checking the correctness of Coulomb corrections as used in superallowed β decay studies aiming at a test of the Constant Vector Current (CVC) hypothesis. Furthermore, $^{32}$Ar is essential for the determination of the kinematics in a recent ISOLDE experiment searching for the limits of scalar currents in weak interaction. An experimental mass accuracy of about 3 keV or better is desired and can be achieved by Penning trap mass spectrometry as performed with ISOLTRAP.

# 2. Motivation

### 2.1 Test of Isobaric-Multiplet-Mass Equation

The concept of isobaric spin or isospin is one of the basic ingredients of nuclear physics, derived from the charge independence of nuclear interaction. In principle every nuclear state with an isospin $T$ is a member of a $2T + 1$ multiplet of ‘analogue’ levels with different charges, measured by the z component $T_z$ of the isospin. For lighter nuclei, these isobaric analogue states have nearly identical wave functions and the effect of the charge dependent forces on their energy can be calculated to good approximation in first-order perturbation theory. As noted first by Wigner [1], the masses of these levels in an isospin multiplet can be given by a very simple quadratic relationship

$$M = a + bT_Z + cT_Z^2 \ , \quad (1)$$

which is today known as the Isobaric-Multiplet-Mass-Equation (IMME). This relation has been subject of a number of theoretical and experimental studies, which can be found summarized in a review by Benenson and Kashy in 1979 [2]. At that time, mostly quartets were known, and it was found that IMME worked extremely well for 21 of 22 examined quartets (including both, ground state and excited state multiplets). The only exception was the A = 9 ground state multiplet, which was furthermore the most accurately known one. Already at that time the possible need for an additional cubic term $d{\cdot}T_z^3$ was discussed but no theoretical justification was found (see discussion in [2]).

In the following years, due to the lack of experimental data, IMME was used as a tool to deduce masses and level energies for proton-rich members of multiplets. A recent example, discussed in more detail below, is an experiment searching for scalar currents [3]. There, a mass value deduced by IMME was used to determine the kinematics of the β-delayed proton decay of $^{32}$Ar.

The most recent compilation of isospin multiplets can be found in ref. [4]. Within the 18 completely measured (ground state) quartets the only significant exception listed there is still the $T = 3/2$, $A = 9$ quartet, for which a $d$ coefficient of $d = 5.5 \pm 1.8$ keV is required.

At the end of last year, ISOLTRAP performed a test run on Argon isotopes. Several isotopes were studied including $^{33}$Ar, which has a half-life of only 173 ms. With this measurement the experimental uncertainty for the mass value of $^{33}$Ar was improved by a factor of seven to reach δm = 4.2 keV [5]. The ISOLTRAP result has now made the $A = 33$

quartet to the most accurately known isospin quartet. A surprise is, that this quartet requires a *d* coefficient with a value of $d = -3.0 \pm 0.9$ keV, which is significantly off from zero.

Figure 1 summarizes the present status of IMME. Taking the available data [4,5] for the ground state quartets and applying the cubic form of IMME to these data gives *d* coefficients and their uncertainties as shown in fig. 1(a). Note the very small uncertainty ($\delta d = 0.9$ keV) for A=33, which is due to the ISOLTRAP result. Figure 1(b) shows the absolute values of *d*, divided by their $1\sigma$ uncertainties $\delta d$. In four out of 18 cases there is a $2\sigma$ significance for a non-zero *d* coefficient. Outstanding are A=9 and A=33. Already from this picture one may conclude, that care has to be taken if quadratic IMME is used for local mass predictions.

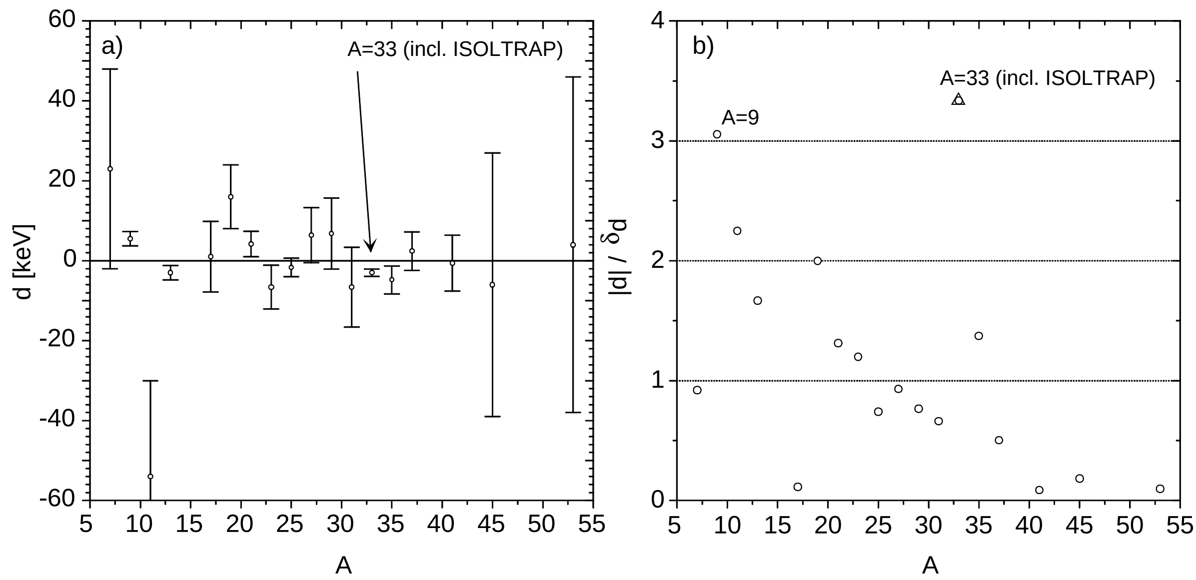


Fig. 1. *d* coefficient of IMME for all 18 measured ground state quartets (a) and the significance of their deviation from zero (b), plotted as a function of the mass number of the quartet. Data from [4] and ISOLTRAP ($^{33}$Ar) [5].

In view of its importance, we propose to study $^{33}$Ar once more, in order to confirm our present result. Since possible with a limited effort, we even aim at a reduction of the mass uncertainty of $^{33}$Ar by another factor 1.5 ... 2, so that it will be comparable to the uncertainties of the other members of the quartet. Other stringent tests for IMME are provided by the isospin quintets, where only 9 completely measured cases are known. $^{32}$Ar is the member of such a quintet. The masses of the other members of the A = 32 quintet are known with an accuracy of ~2 keV ($^{32}$Cl, $^{32}$Si) and ~0.4 keV ($^{32}$P, $^{32}$S), while the present uncertainty of the $^{32}$Ar mass is 50 keV. Therefore, the proposed measurement (see Section 2.3) of the mass of this candidate with an accuracy of a few keV would provide a further chance to verify the validity of IMME.

### 2.2 Coulomb-corrections to $0^+ \rightarrow 0^+$ Ft values

Superallowed Fermi $0^+ \rightarrow 0^+$ nuclear $\beta$ decays provide presently the best test of the Conserved Vector Current hypothesis in weak interaction and, together with the muon lifetime, the most accurate value for the up-down quark-mixing matrix element of the Cabibbo-Kobayashi-Maskawa (CKM) matrix [6-9]. The CVC hypothesis postulates that the matrix elements of super-allowed $0^+ \rightarrow 0^+$ Fermi transitions should all be equal and independent of nuclear structure apart from small terms for nucleus-dependent radiative correction $\delta_R$ and for Coulomb correction $\delta_C$. If this is true, the experimental *ft* values that include isospin mixing and radiative corrections (*Ft*), allow an accurate determination of the weak vector coupling constant $G_V$. Up to now, super-allowed (T=1) $0^+ \rightarrow 0^+$ transitions have been measured to a precision of 0.1 % or better in the decays of nine nuclei between $^{10}$C and $^{54}$Co [10]. Using these data, the present nuclear β decay result differs at the 98 % confidence level from the unitarity condition of the CKM matrix. The uncertainty quoted for $V_{ud}$ is largely due to theoretical corrections for $\delta_R$ and $\delta_C$. Recent free neutron decay data for $V_{ud}$ [9] imply also a disagreement with unitarity in accordance with the nuclear β decay data.

Experimentally, the true *Ft* –value is obtained via $Ft$ = ft $(1+\delta_R)$ $(1-\delta_C)$ = K / $G_V^{'2}$, where f is the statistical rate function, t is the partial half-life, $\delta_R$ is the nucleus-dependent radiative correction, $\delta_C$ is the correction for Coulomb effects or isospin mixing, and K is a constant. The quantity $G_V^{'2}$ is the effective vector coupling constant. The leading terms and the radiative corrections are well-founded [8]. Therefore, attention focuses on the less-understood nuclear-structure dependent Coulomb correction term $\delta_C$.

In order to verify the correctness of the calculated corrections $\delta_C$, it is important to include new super-allowed emitters to the series of already well known transitions. For the nine nuclides listed above the corrections are in the range of $\delta_C$ = 0.16 ... 0.62% with an average of about 0.4% and an assigned uncertainty of 0.03% [11-13]. Good cases for a stringent test of the calculations are those isotopes for which $\delta_C$ is predicted to be even larger. Within the mass range of the nine already well studied nuclides the candidates are $^{30}$S, $^{34}$Ar, and $^{38}$Ca. For these, the corrections are expected to be $\delta_C$ = 1.2(1)%, 1.0(1)%, and 0.9(1) % [8].

The present uncertainty of the ft value of $^{34}$Ar is about 0.6%, a factor of 6 and more larger than that of the nine well studied transitions. In order to reach an uncertainty in the ft-value of 0.1% or less, an accuracy of 1 keV or better is required for the Q-value of the decay of $^{34}$Ar. The mass of $^{34}$Ar is presently known with an uncertainty of δm = 3 keV, that of $^{34}$Cl with δm = 0.1 keV. Hence, a mass determination of $^{34}$Ar with an accuracy of better than δm = 1 keV is required [14].

It is expected that the half-life and branching ratio will be determined precisely enough in the near future. Work in this direction is already planned at Texas A&M by J. Hardy et al., but was yet not given high priority due to the too large mass uncertainty of $^{34}$Ar [14].

### 2.3 Search for scalar currents in weak interaction – kinematics in e-ν correlation studies

According to the Standard Model, nuclear β decay is mediated by the exchange of W bosons which have only vector and axial vector couplings. Extensions to the Standard Model, however, predict the existence of scalar and tensor couplings in weak interaction. A possibility to search for these currents is the precise measurement of the e-ν correlation in pure Fermi or GT decays. Since the e-ν correlation can not be directly observed, the correlation between the electron or positron and the recoiling daughter nucleus is used.

Searching for scalar currents, an experiment of this kind was recently carried out at ISOLDE by studying the $0^+ \rightarrow 0^+$ β decay of $^{32}$Ar [3]. The effect of the positron recoil on the shape of the narrow proton group following the superallowed decay was analysed with high precision. From a comparison of this experimentally determined shape with the linear superposition of the shapes theoretically expected for pure vector and pure scalar interaction, a limit for the existence of the latter was deduced.

An important parameter in the evaluation of this e-ν correlation experiment is the velocity of the recoiling daughter nucleus, which is determined by the Q-value of the β decay, and hence by the masses of parent and daughter nucleus. The mass of $^{32}$Ar is known with an uncertainty of 50 keV. Using this value would have imposed an uncertainty of 6% on the correlation coefficient. Therefore, the result of an IMME mass prediction with an uncertainty of 2.2 keV was used instead. This gave a constraint of 0.1% on the existence of scalar currents [3].

Facing the strong additional evidence, provided by the recent ISOLTRAP measurement, that IMME may not be as reliable as formerly assumed in this region of nuclei, it is mandatory to perform a precision mass measurement on $^{32}$Ar. Then a purely experimental mass value is available for the determination of the e-ν correlation coefficient.

As suggested by A. Garcia [15], $^{32}$Ar and $^{33}$Ar may also be used to test Coulomb corrections calculated for the Fermi decay of these isotopes. $^{32}$Ar and $^{33}$Ar are predicted to have $\delta_C \approx 2\%$ and 1.2%. Again half-lives, branching ratios and masses are required. For $^{33}$Ar, which has a mixed Fermi/GT transition, the Fermi strength can be extracted from the e-ν correlation obtained at ISOLDE for $^{33}$Ar. However, mass accuracies of less than 3 keV would be required to test whether the calculated corrections are accurate within 50%.

## 3. Mass measurements

The Penning trap mass spectrometer ISOLTRAP is in operation at ISOLDE since many years. It has undergone continuous improvement and today consists of a linear RFQ ion cooler and buncher and two Penning traps [16,17]. The RFQ ion cooler and buncher is based on a linear gas filled RFQ ion trap and serves for an efficient conversion of the continuous ISOLDE beam into cooled ion bunches. These bunches are captured in the first Penning trap, which can be operated as an isobar separator. The ions are again cooled in a buffer gas and then sent to the second Penning trap, which is the actual mass spectrometer. Here, the mass measurement is carried out via a determination of the cyclotron frequency $\omega_C = q/m \cdot B$ of ions with a charge-over-mass ratio q/m stored in a magnetic field $B \cong 6$ T.

The Penning trap technique offers the unique advantage, that the ions are stored in a very small volume and that the electromagnetic fields determining the cyclotron frequency of the ions can be very well controlled. Hence, systematic errors are very small. The largest contribution is the stability of the magnetic field. If a magnetic field calibration is performed every 5-8 hours then the systematic error can be constraint to be not larger than $1 \cdot 10^{-7}$. Tests have shown that this uncertainty can be considerably reduced down to a level of a few $10^{-8}$ by more frequent magnetic field calibration (every 2-3 hours) [18].

To date the ISOLTRAP experiment has very successfully measured masses of more than 150 unstable isotopes [19,20]. An accuracy of $\delta m/m = 1 \cdot 10^{-7}$ (corresponding to $\delta m < 10$ keV for $A < 100$) is typically achieved. Most of the investigated isotopes have half-lives larger than 1s. As mentioned above, in 1999 it was possible to demonstrate in the case of $^{33}$Ar that the technique can very well be applied to isotopes with half-lives in the 100 ms range [5]. There are two main reasons why such measurements have now become feasible: the efficiency of ISOLTRAP has been greatly improved by the installation and successful operation of the ion beam cooler and buncher and scenarios for a very fast handling of the ions in the spectrometer were developed.

The statistical uncertainty $\delta m/m$ of a mass determination by ISOLTRAP depends mainly on the number N of detected ions and on the resolving power $R=\nu_c/\Delta\nu_c(\text{fwhm})$ with which the measurement is performed. A rule of thumb for the statistical ($1\sigma$) accuracy achievable with ISOLTRAP is $\delta m/m = 1 \cdot R^{-1} \cdot N^{-1/2}$.

The resolving power R is depending on the line width $\Delta\nu_c(\text{fwhm}) = 0.9/T_{obs}$ of the observed cyclotron resonances, which is determined by the "observation" time $T_{obs}$ of the ion motion in the trap. From this, it becomes clear that for very short-lived isotopes the resolving power is limited. However, it is not determined by the half-life but by the fact that at least one stored ion must have survived the total observation time without decay. In practice, values of up to $T_{obs} = 3{\cdot}T_{1/2}$ seem to be reasonable.

<u>$^{32}$Ar and $^{33}$Ar measurements</u>

For the mass measurement of $^{32}$Ar ($T_{1/2}$ = 98 ms) the following scenario can be envisaged. An observation time $T_{obs}$ = 100 ms of about 1 half-live will yield a resolving power of R = (2.9 MHz/10 Hz) ≈ 300000. Then, a statistical accuracy of $\delta m/m \approx 1{\cdot}10^{-7}$ will already be achieved with about 1100 detected ions.

The release curve for $^{32}$Ar shows that more than 50% of the ions are delivered within a period of 100 ms somewhat delayed after the proton pulse. Therefore, an accumulation time in the RFQ ion cooler and buncher of about 100 ms is reasonable. The time needed for isobar separation and cooling in the first Penning trap is 70 ms. Together with the time $T_{obs}$ = 100 ms for the cyclotron frequency determination, this adds up to a total time of 270 ms that the ions spend in the spectrometer. A decay loss factor of 0.15 has therefore to be considered.

The total efficiency of ISOLTRAP is given by the detection efficiency of ~30% of the ion detector (MCP) and by the transport efficiency of the spectrometer. The latter can be divided into that of the ion cooler and buncher and that of the tandem Penning trap system. The cooler and buncher efficiency was determined to be ~15%. A transfer-efficiency between the Penning traps of close to 100% has been verified. The fact that under on-line conditions not all ion optical parameters in this rather complex system may have their optimum value will be accounted for by an additional loss factor of 10. This gives an effective total efficiency, including the decay losses, of about $10^{-3}$.

The ISOLDE yield for $^{32}$Ar reported so far for a CaO target is ~100 atoms/proton pulse. Aiming at mass uncertainty of $\delta m/m \approx 1{\cdot}10^{-7}$ for $^{32}$Ar a statistical uncertainty of $0.5{\cdot}10^{-7}$ is desirable. This can be achieved with about 50 000 proton pulses (4 shifts). For the beam time requirements, the frequent intermediate magnetic field calibration measurements and further systematic tests have to be considered. Therefore, in total eight shifts are required to determine the mass of $^{32}$Ar with the desired accuracy of about 3 keV.

For the measurement of $^{32}$Ar the use of the HRS will be required with a moderate resolving power of about 7000-8000 in order to suppress the strong beam contamination with $O_2^+$ (typically a few ten pA). This is too much to be handled by the isobar separator Penning trap, but together with the HRS very clean $^{32}$Ar samples can be prepared for the mass measurements.

Compared to $^{32}$Ar the mass measurement is considerably easier in the case of $^{33}$Ar due to the longer half-life and the higher yield. Using a similar, but slightly prolonged measurement cycle ($T_{obs}$ = 200 ms, R = 500000), it is possible to improve the accuracy of the present result by about a factor of 2 and to reach $\delta m \approx 2$ keV for $^{33}$Ar. From the experience of the previous experiment on this isotope, this should be accomplishable within 3 shifts of beam time.

$^{34}$Ar measurement

The measurement of $^{34}$Ar aims for a mass accuracy of $\delta m < 1$ keV. Due to the long half-life of 845 ms this isotope can be studied with a resolving power of 2.5 million. The comfortable yields of $\approx 10^5$/s will allow to acquire the necessary statistics in a short time and furthermore to perform a number of systematic tests. In the case of a measurement at such high accuracy level, these tests are needed to put constraints on possibly undetected systematic errors. Including the magnetic field calibrations, which will be carried out every hour, 3 shifts of beam time are required for this measurement.

## 4. Beam request

It is proposed to perform this measurement series in 2 separate beam times. The first beam time will allow to complete the high precision investigation of $^{34}$Ar and $^{33}$Ar. Furthermore, measurements on $^{32}$Ar will be started in order to get experience with this isotope, a preliminary $^{32}$Ar mass value with $\delta m \approx 10$ keV should be achievable. The second beam time will then be fully devoted to the study of $^{32}$Ar aiming at $\delta m \approx 3$ keV.

Before each beam time 1.5 shifts of stable Ar beam will be required for beam line and spectrometer tuning.

| | # of shifts |
|---|---|
| stable beam (Ar) | 1.5 |
| $^{34}$Ar and $^{33}$Ar measurement<br>$^{32}$Ar test measurement | 6<br>2 |

| | |
|---|---|
| stable beam (Ar) | 1.5 |
| $^{32}$Ar measurement | 6 |

| | |
|---|---|
| Total | 17 |

| | |
|---|---|
| Separator: | HRS |
| Target: | CaO |
| Ion Source: | Plasma + cold line |

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