Test of IMME in $fp$ shell via direct mass measurements of $T_z = -\frac{3}{2}$ nuclides

Y H Zhang$^1$, H S Xu$^1$, Yu A Litvinov$^{1,2}$, X L Tu$^1$, X L Yan$^{1,3}$, S Typel$^2$, K Blaum$^2$, M Wang$^{4,5}$, X H Zhou$^1$, Y Sun$^{6,1}$, B A Brown$^7$, Y J Yuan$^1$, J W Xia$^1$, J C Yang$^1$, G Audi$^4$, X C Chen$^{1,3}$, G. B. Jia$^{1,3}$, Z G Hu$^1$, X W Ma$^1$, R S Mao$^1$, B Mei$^1$, P Shuai$^9$, Z Y Sun$^1$, S T Wang$^{1,3}$, G Q Xiao$^1$, X Xu$^{1,3}$, T Yamaguchi$^9$, Y Yamaguchi$^{10}$, Y D Zang$^{1,3}$, H W Zhao$^1$, T C Zhao$^1$, W Zhang$^{1,3}$, W L Zhan$^1$

$^1$Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, People’s Republic of China
$^2$GSI Helmholtzzentrum für Schwerionenforschung, Planckstraße 1, 64291 Darmstadt, Germany
$^3$Graduate University of Chinese Academy of Sciences, Beijing, 100049, People’s Republic of China
$^4$Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany
$^5$CSNSM-IN2P3-CNRS, Université de Paris Sud, F-91405 Orsay, France
$^6$Department of Physics, Shanghai Jiao Tong University, Shanghai 200240, People’s Republic of China
$^7$Department of Physics and Astronomy and National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA
$^8$Department of Modern Physics, University of Science and Technology of China, Hefei 230026, People’s Republic of China
$^9$Department of Physics, Saitama University, Saitama 338-8570, Japan
$^{10}$RIKEN Nishina Center, RIKEN, Saitama 351-0198, Japan

E-mail: yhzhang@impcas.ac.cn, hushan@impcas.ac.cn, y.litvinov@gsi.de

Abstract. Isochronous mass spectrometry has been applied to neutron-deficient $^{58}$Ni projectile fragments at the HIRFL-CSR facility in Lanzhou, China. Masses of four short-lived $T_z = -\frac{3}{2}$ nuclides $^{41}$Ti, $^{45}$Cr, $^{49}$Fe, and $^{53}$Ni have been measured with a precision of 20 – 40 keV. The new mass data enabled for the first time to test the isobaric multiplet mass equation (IMME) in $fp$-shell nuclei. We observed that the IMME is inconsistent with the generally accepted quadratic form for the $A = 53$, $T = 3/2$ quartet. We performed full space shell model calculations and compared them with the new experimental results. The main results were published in Y.H. Zhang et al., Physical Review Letters 109 (2012). Here we give details on the experiment and data analysis as well as summarize the main findings.

1. Introduction

Isospin symmetry is a fundamental concept in nuclear and particle physics. All states in a nucleus composed of $Z$ protons and $N$ neutrons have the same isospin projection defined as $T_z = (N - Z)/2$ but they can have different total isospin $T = |N - Z|/2, |N - Z|/2 + 1, \ldots$. For a set of isobaric nuclei, the states with same $T$ and $J^\pi$ are called isobaric analog states.
The IAS have very similar structure and properties. They are energetically degenerate in the absence of any charge-dependent nucleon-nucleon interaction when the neutron-proton mass difference is corrected for. Assuming the two-body nature for any charge-dependent effects and the Coulomb force between the nucleons, Wigner [1] as well as Weinberg and Treiman [2] noted that masses, \( m \), of the \( 2T + 1 \) members of an isobaric multiplet are related by the isobaric multiplet mass equation (IMME):

\[
\text{ME}(A, T, T_z) = a(A, T) + b(A, T)T_z + c(A, T)T_z^2,
\]

where \( \text{ME} = (m - A \cdot u) \epsilon^2 \) is the mass excess value and \( a, b, c \) are parameters depending on the atomic mass number \( A \) and the total isospin \( T \). This mass equation is the most basic prediction to follow from the concept of isospin in nuclear physics. Our main aim is to test its validity on the basis of new masses of exotic nuclei measured by us. If the experimental data are not described by the parabolic function (1), then extra terms like \( dT_z^3 \) or \( eT_z^4 \) can be added to IMME in order to provide a measure of any deviation from the quadratic form. Numerous measurements have been performed investigating the validity of IMME. Corresponding reviews and compilations of existing data can be found in Refs. [3, 4].

In recent years, precision tests of IMME have become possible due to access to accurate mass data coming mainly from Penning trap facilities like ISOLTRAP at CERN, Geneva [5], TITAN at TRIUMF, Vancouver [6], JYFLTRAP at University of Jyväskylä [7], and LEBIT at Michigan State University [8]. However, up to now the tests have been focused on the light-mass region [9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19]. As a general trend, quadratic form stems well with the data [3, 4], except for slight disagreements at \( A = 8, 9, 32, \) and \( 33 \) [9, 3, 4, 10, 16, 17, 18, 19, 20]. Several explanations for the cubic term in IMME are suggested such as isospin mixing, second-order Coulomb effects, or charge-dependent nuclear forces [9, 20, 21, 22]. To our knowledge, prior to our investigation in Ref. [23], there were no experimental tests of IMME in the \( fp \)-shell. The main reason for this was obviously the lack of accurate mass data on exotic \( T_z = -3/2, -1/2 \) nuclei. According to Henley and Lacy [21], the correction to the quadratic form of IMME with the introduction of a cubic term \( d(A, T)T_z^3 \) in Eq. (1) is proportional to \( Ze(\alpha \) being the fine structure constant). Hence, the effects of isospin mixing and/or charge-dependent nuclear forces may be enhanced in heavy nuclei, which makes our study extremely interesting. We like to stress, that an accurate test of IMME in the \( fp \)-shell is motivated not only by the fundamental importance of isospin symmetry, but also by the requirements of accurate mass predictions for the neutron-deficient nuclei in this region. These masses are indispensable nuclear physics input for the network calculations of astrophysical \( rp \)-process of nucleosynthesis [24]. Although a tremendous progress has been achieved in measuring masses of \( rp \)-process relevant nuclei in the last years, see, e.g., Refs. [25, 26, 27, 28, 29], many nuclides remain unaccessible at the present radioactive beam facilities and their masses still have to be estimated.

In this contribution we present the new mass measurements conducted at the Institute of Modern Physics in Lanzhou, China. Masses of a series of \( T_z = -3/2 \) nuclei from \( ^{41}\text{Ti} \) through \( ^{53}\text{Ni} \) have been determined with high accuracy for the first time. In particular, the masses of \( ^{41}\text{Ti}, ^{45}\text{Cr}, ^{49}\text{Fe} \) and \( ^{53}\text{Ni} \) nuclides enabled us to perform the first experimental test of IMME in the \( fp \)-shell, see Ref. [23]. We observed that for the \( A = 53 \) (\( T = 3/2 \)) quartet IMME is inconsistent at a 3.5\( \sigma \) confidence level with the generally accepted quadratic form. Experimental details as well as the details of data analysis and results are presented.

2. Experiment and results

The experiment was conducted at the Heavy Ion Research Facility in Lanzhou – Cooler-Storage Ring (HIRFL-CSR) accelerator complex [30]. Figure 1 (left) presents the layout of the HIRFL-
CSR facility. The high-energy part of the complex consists of the synchrotron CSSRe, the in-flight fragment separator RIBLL2, and the cooler-storage ring CSSRe [31].

In recent years we developed the isochronous ion-optical mode of CSSRe, the mode which is necessary for the implementation of Isochronous Mass Spectrometry (IMS). The latter is a technique pioneered at GSI Helmholtz Center in Darmstadt for in-ring high-precision mass measurements of short-lived nuclides [32, 33].

In short, the mass-over-charge ratios, \( m/q \), of stored ions in a ring are related to their revolution frequencies (revolution times), \( f(t) \), as [34]:

\[
\frac{\Delta t}{t} = \frac{\Delta f}{f} = \frac{1}{\gamma^2} \frac{\Delta (m/q)}{m/q} - \frac{\Delta v}{v} \left(1 - \frac{\gamma^2}{\gamma^2}ight),
\]

where \( \Delta v/v \) is the velocity spread of the ions which is in the order of a few percent due to the nuclear reaction process, \( \gamma \) is the relativistic Lorentz factor and \( \gamma \approx 1.4 \) is an ion optical parameter, the so-called transition point of CSSRe, see Ref. [35] for more details. In the IMS, the energies of the injected ions have to fulfill \( \gamma = \gamma_t \) and thus the second term on the right hand side disappears. Physically this means that the velocity spread of injected ions is compensated by their orbit lengths. As a result, the revolution time of the ion becomes a direct measure of its mass-over-charge ratio [34]. In our recent experiments, nuclei of interest were produced by employing projectile fragmentation reactions. The results of our mass measurements of short-lived neutron-deficient nuclides are summarized on the chart of the nuclides illustrated in Figure 1 (right) [23, 28, 36, 37, 38].

---

**Figure 1.** The layout of HIRFL-CSR accelerator complex in Lanzhou [30]. The results of isochronous mass measurements for short-lived neutron-deficient nuclides using CSSRe are also in the insert [23, 28, 36, 37, 38].
Figure 2. (a) The revolution time spectrum zoomed in the time window of 608 ns ≤ t ≤ 620 ns. The insert shows the well-resolved peaks of $^{30}\text{S}^{16+}$ and $^{45}\text{Cr}^{24+}$ nuclei, which have similar m/q values. Nuclei with masses determined in this experiment and those used as references are indicated with bold and italic letters, respectively. (b) Standard deviations of the revolution time peaks for the stored ions in the entire measured range of revolution times.

In the present experiment we aimed at mass measurements of short-lived $T_z = -3/2$ nuclei. We used $^{58}\text{Ni}$ primary beams, which were accelerated by CSRm to 463.36 MeV/u, fast extracted and focused on a ~15 mm $^{9}\text{Be}$ production target located in front of the RIBBL2. At this energy, the reaction products emerge from the target as bare nuclei, i.e., with no atomic electrons. After the in-flight separation with RIBLL2, the cocktail beam of exotic nuclei within a $B\rho$-acceptance of about ±0.2% was injected into CSRe. Both RIBLL2 and CSRe were set to a fixed magnetic rigidity of $B\rho = 5.6770$ Tm to allow for an optimal transmission of the $T_z = -3/2$ nuclides centered around $^{47}\text{Mn}$. Other nuclides within the acceptance of the RIBLL2-CSRe system were transmitted and stored as well. Typically, about ten ions were stored simultaneously from each injection.

To measure revolution times of stored ions, we used a timing detector [39], which is equipped with a 19 $\mu$g/cm$^2$ carbon foil of 40 mm in diameter and installed inside CSRe aperture. Secondary electrons were released from the foil at each passage of every stored ions. The electrons were guided to a set of micro-channel plates (MCP), thus giving timing signals. The latter were directly sampled using a digital oscilloscope Tektronix DPO 71254. For each injection the recording time was set to 200 $\mu$s corresponding to ≈320 revolutions of the ions. The time resolution of the detector was about 50 ps, and the detection efficiency was found [39] to vary from about 20% to about 70% depending on the ion type and the number of stored ions. The periodic timing signals were used to determine the revolution time of each individual ion. Only the ions which were stored for more than 300 revolutions in CSRe were used in the analysis. This condition is important for the precise determination of the corresponding revolution times. All obtained values were put into a histogram thus forming a revolution-time spectrum. More details can be found in Ref. [28, 40].

The resolving power of CSRe mass spectrometry is determined by the instabilities of magnetic fields which cause small shifts of the entire revolution time spectra measured for different injections (see Ref. [40]). Compared to our previous measurements [28, 40], the stability of the magnets has been improved significantly isolating. Furthermore, the magnetic fields of
Table 1. Experimental ME values obtained at CSRe and values from the updated atomic-mass evaluation AME'11 [43]. The extrapolated values are indicated with symbol “#”. The deviations \( \delta \) are calculated as \( \delta = \text{ME}_{\text{CSRe}} - \text{ME}_{\text{AME'11}} \). Also listed are the numbers of identified ions \( N \), standard deviations \( \sigma_t \) and FWHM values of the revolution time peaks (see Fig. 2). The latter are converted in keV via \( \text{FWHM} = \frac{2.36 \cdot q \cdot (a_1 + 2a_2 \cdot t + 3a_3 \cdot t^2)}{\sigma_t} \), where \( a_1, a_2 \) and \( a_3 \) are the free parameters of the calibration fit.

| Atom  | \( N \) | \( \sigma_t \) (ps) | FWHM (keV) | ME\(_{\text{CSRe}}\) (keV) | ME\(_{\text{AME'11}}\) (keV) | \( \delta \) (keV) | Ref. |
|-------|--------|---------------------|------------|--------------------------|--------------------------|-----------------|------|
| \(^{41}\text{Ti}\) | 76     | 2.0                 | 580        | -15698(28)               | -15090(363)               | -608(364)       | [23] |
| \(^{45}\text{Cr}\) | 218    | 2.2                 | 702        | -19515(35)               | -19403(196)#             | -112(199)       | [38] |
| \(^{49}\text{Fe}\) | 338    | 3.0                 | 1026       | -24751(24)               | -24824(149)#             | 73(151)         | [23] |
| \(^{53}\text{Ni}\) | 651    | 4.1                 | 1488       | -29631(25)               | -29687(298)#             | 56(299)         | [23] |

CSRe dipole magnets were constantly monitored using a Hall probe. This information was used to identify time intervals of relatively constant magnetic fields. Different from the data analysis described in Ref. [40], the entire data were grouped according to these time intervals. In total 761 independent sub-spectra were obtained. Each spectrum corresponds to about 100 injections into CSRe. Taking the relative shifts between individual spectra into account, the 761 sub-spectra were combined into a common revolution time spectrum. Figure 2 illustrates a part of this spectrum zoomed in a time window of 608 ns \( \leq t \leq 620 \) ns. The identification of the peaks in the spectrum was done in the same way as in Refs. [33, 40, 41].

The experiment was running for about 5 days, during which we have accumulated 76, 218, 338, and 651 valid events corresponding to stored \(^{41}\text{Ti}^{22+}, \(^{45}\text{Cr}^{24+}, \(^{49}\text{Fe}^{26+}, \) and \(^{53}\text{Ni}^{28+}\) ions, respectively. The standard deviations of the revolution-time peaks in this time range lie within \( 2 \sim 5 \) ps and the achieved mass resolving power amounts to \( m/\Delta m = 180000 \). This time window has been used to determine the mass values of \(^{41}\text{Ti}, \(^{45}\text{Cr}, \(^{49}\text{Fe} \) and \(^{53}\text{Ni}\).

In order to calibrate the spectrum, fourteen nuclides with accurately known masses (see Fig. 2), taken from the updated Atomic Mass Evaluation [42, 43], were used to fit their \( m/q \) values versus their revolution times \( t \). A third order polynomial function has been employed for the fitting. The unknown mass values of \(^{41}\text{Ti}, \(^{45}\text{Cr}, \(^{49}\text{Fe} \) and \(^{53}\text{Ni} \) were determined by interpolating the fit function to the corresponding times \( t \).

In order to estimate possible systematic errors, we re-determined the ME values of each of the fourteen reference nuclides by calibrating the spectrum with the other thirteen nuclides. The agreement between our re-determined ME values and the corresponding ones from literature has been examined by calculating the normalized \( \chi \)-value, defined as \( \chi_n = \sqrt{\chi^2/n} \) with \( n = 14 \) in our case, in the same way as in our previous measurements [28, 40]. The obtained \( \chi_n = 1.18 \) is within the expected range of \( \chi_n = 1 \pm 0.19 \) at 1\( \sigma \) confidence level, indicating that no additional systematical errors have to be considered. The ME values of \(^{41}\text{Ti}, \(^{45}\text{Cr}, \(^{49}\text{Fe} \) and \(^{53}\text{Ni} \) determined in this work are listed in Table 1.

A low-lying isomeric state in \(^{45}\text{Cr} \) (\( E_x = 107 \) keV, \( T_{1/2} > 80 \) \( \mu \)s) has been reported in Ref. [44]. This isomer cannot be resolved in our spectra (see the insert in Figure 2). Therefore, a dedicated analysis was conducted to account for a possible contamination by the isomer. Details of the analysis and the error propagation will be reported elsewhere [38]. The outcome is to increase the uncertainty from 20 to 35 keV.

We note a striking disagreement of our ME\(^{41}\text{Ti}\)= \(-15698(28)\) keV with the tabulated value in Ref. [43]. Our value is in excellent agreement with ME\(^{41}\text{Ti}\)= \(-15700(100)\) keV recommended in the Atomic Mass Evaluation 2003 (AME’03) [42]. However, it differs largely

\[ \text{Journal of Physics: Conference Series} \]
Table 2. Taken from Ref. [23], compilation of ME values for ground states (g.s.), isobaric analog states (IAS) and the corresponding excitation energies ($E_x$) for $A = 41, 45, 49, \text{and } 53$ ($T = 3/2$) quartets. Also listed are $\chi_n$-values for quadratic fits and $d$-coefficients for cubic fits (see text).

| Atom    | $T_z$ | ME(g.s) ($E_x$ keV) | ME(IAS) ($E_x$ keV) |
|---------|-------|--------------------|--------------------|
| $^{53}$Ni | $-3/2$ | $-29631(25)$ [23] | 0  | $-29631(25)$ |
| $^{53}$Co | $-1/2$ | $-42658.6(17)$ [43] | 4393(19) [47] | $-38266(19)$ [47] |
| $^{53}$Fe | $+1/2$ | $-50946.7(17)$ [43] | 4250(3) [46] | $-46696.7(34)$ |
| $^{53}$Mn | $+3/2$ | $-54689.0(6)$ [43] | 0  | $-54689.0(6)$ |
| Quadratic fit: $\chi_n = 3.7$ |
| Cubic fit: $d = 39(11)$ |
| $^{49}$Fe | $-3/2$ | $-24751(24)$ [23] | 0  | $-24751(24)$ |
| $^{49}$Mn | $-1/2$ | $-37615(24)$ [43] | 4809(28) [47] | $-32806(15)$ [47] |
| $^{49}$Cr | $+1/2$ | $-45333(2)$ [43] | 4764(5) [46] | $-40569(5)$ |
| $^{49}$V | $+3/2$ | $-47961.0(9)$ [43] | 0  | $-47961.0(9)$ |
| Quadratic fit: $\chi_n = 1.5$ |
| Cubic fit: $d = 13.2(8.9)$ |
| $^{47}$Cr | $-3/2$ | $-19515(35)$ [23] | 0  | $-19515(35)$ |
| $^{47}$V | $-1/2$ | $-31880(17)$ [43] | 4791(19) [47] | $-27089(9)$ [47] |
| $^{47}$Ti | $+1/2$ | $-39008.3(8)$ [43] | 4723(7) [46] | $-34285(7)$ |
| $^{47}$Sc | $+3/2$ | $-41070.4(6)$ [43] | 0  | $-41070.4(6)$ |
| Quadratic fit: $\chi_n = 0.7$ |
| Cubic fit: $d = 5.4(8.2)$ |
| $^{45}$Ti | $-3/2$ | $-15698(28)$ [23] | 0  | $-15698(28)$ |
| $^{45}$Sc | $-1/2$ | $-28642.41(8)$ [43] | 5937(3) [47] | $-22705(3)$ [47] |
| $^{45}$Ca | $+1/2$ | $-35137.92(14)$ [43] | 5819(2) [46] | $-29320(2)$ |
| $^{45}$K | $+3/2$ | $-35559.544(4)$ [43] | 0  | $-35559.544(4)$ |
| Quadratic fit: $\chi_n = 0.6$ |
| Cubic fit: $d = -2.8(5.0)$ |

from ME($^{41}$Ti) = $-15090(360)$ keV measured in the storage ring ESR of GSI using the same IMS technique [45]. Compared to Ref. [45], we accumulated by a factor of 15 larger counting statistics for $^{41}$Ti, achieved by a factor of 1.6 higher mass resolving power, and, very essentially, we have used 14 well-known reference masses instead of 4, which provide a much more robust calibration of the spectra.

3. Test of IMME in $fp$ shell

To test the validity of the quadratic form of IMME, the energies of four members of a $T = 3/2$ multiplet are required. These are the mass values of the ground states of $T_z = \pm 3/2$ nuclei and the IAS energies of the $T_z = \pm 1/2$ nuclei. Note, that the spin and parity of the $T = 3/2$ IASs for $A = 45, 49, \text{and } 53$ are $J^n = 7/2^-$ and for $A = 41$ they are $J^n = 3/2^+$. With our new mass values, the data of four $T = 3/2$ isospin quartets at $A = 41, 45, 49, \text{and } 53$ could be completed. All available experimental data for these multiplets are compiled in Table 2 (see Ref. [23]). The mass values for the ground states are from our measurements and from Ref. [43]. The IAS excitation energies in the $T_z = +1/2$ nuclei are from compilation [46]. The data for the $T_z = -1/2$ nuclei were obtained in Ref. [47] from measurements of $\beta^+$-delayed protons of the respective $T_z = -3/2$ nuclei. Please note, those listed in Table 2, ME(IAS) and
Figure 3. $d$ coefficients for the four $T = 3/2$ isobaric multiplets in $fp$-shell (squares). Experimental data since 2001 (circles) [13, 14, 15, 16] are shown for comparison. Please note, that albeit with large uncertainties, there seems to be a trend of gradual increase of $d$ with $A$ in $fp$ shell.

$E_x$ values from Ref. [47], are updated here taking into account the most recent ground-state masses compiled in Ref. [43].

Assuming the quadratic form of IMME (see Eq. (1)), the fit results for $A = 41, 45,$ and 49 have reasonable $\chi_n$ values (see Table 2). A striking result of $\chi_n = 3.7$ is obtained for the $A = 53, T = 3/2$ isobaric multiplet. This corresponds to a probability of 0.02% that the data can be described by Eq. (1). Therefore, we added a cubic term $d T^3$ in Eq. (1) and derived all four coefficients from the four ME values. The obtained $d$ coefficients are given in Table 2 and presented in Figure 3 together with recent precision tests in the $sd$-shell nuclei [13, 14, 15, 16]. For the $A = 53$ ($T = 3/2$) quartet we obtain $d = 39(11)$ keV which deviates by $3.5\sigma$ from zero thus indicating a dramatic failure of the quadratic form of IMME.

In order to explain the observed $d$-coefficient for $A = 53$, we have performed theoretical calculations employing the $f_{7/2}$ as well as the full ($f_{7/2}, f_{5/2}, p_{3/2}, p_{1/2}$) ($fp$) model space. The former calculations are based on Ref. [48], where the $(f_{7/2})^2$ two-body matrix elements for the proton-proton, neutron-neutron and proton-neutron interactions were obtained from a fit to the isobaric displacement energies in nuclei with $A = 41 \sim 55$. In the latter, the Hamiltonian is composed of the GPFX1A isospin conserving Hamiltonian [49, 50, 51] plus the Ormand-Brown (OB) isospin non-conserving Hamiltonian [52]. Details of the GPFX1A part and its applications to many $fp$ shell data are given in Refs. [49, 50, 51]. The OB part was obtained from a consideration of Coulomb, charge-symmetry breaking and charge-dependence breaking interactions with strengths determined from the data available for nuclei with $A = 41 \sim 59$. The theoretical values $d(f_{7/2}) = -0.5$ keV and $d(fp) = -1.0$ keV do not agree with experiment.

The numerical errors in the computation of the $d$ coefficients are less than one keV. The main theoretical error in these calculations comes from the position of the $T = 1/2$ states. There are several nearby $T = 1/2$ states that could mix with the $T = 3/2$ state with a level density of about one per 150 keV. But the typical isospin mixing matrix element is on the order of 5 keV or less, so it is impossible to get an energy shift of the $T = 3/2$ state due to two-level mixing of more than about 5 keV. The largest experimental uncertainty comes from the determination of the excitation energy of the $T = 3/2$ state in $^{53}$Co obtained from the energy of $\beta^+$-delayed protons of $^{53}$Ni [47]. To change the $d$(exp) value from 39 keV to zero, the proton energy would require to be lowered by 78 keV from 1929 keV to 1851 keV. Therefore, it is highly desirable to perform independent mass measurements as well as a new proton-decay experiment with a higher resolution in order to verify the obtained experimental results for $A = 53$. 

11th International Conference on Nucleus-Nucleus Collisions (NN2012) IOP Publishing
Journal of Physics: Conference Series 420 (2013) 012054 doi:10.1088/1742-6596/420/1/012054
4. Summary and conclusions
In summary, we have accurately measured masses of a series of $T_z = -3/2$ nuclei from $^{41}$Ti through $^{53}$Ni. This allowed us for the first time to perform a test of IMME in $fp$-shell nuclei. We found a breakdown of the quadratic form of IMME for the $A = 53$ ($T = 3/2$) quartet. The disagreement cannot be explained by neither the existing nor the new theoretical calculations of isospin mixing. This result calls for more precise measurements of the ground-state mass of $^{53}$Ni and of the excitation energy of the isobaric analog state in $^{53}$Co up to a precision of a few keV. If this breakdown can be confirmed by improved experimental data (ground-state masses, energies of the IAS), possible reasons, such as enhanced effects of isospin mixing and/or charge-dependent nuclear forces in the $fp$-shell, should be investigated.

5. Outlook
In the last few years at HIRFL-CSRe we have successfully established the research program on direct mass measurements employing isochronous mass spectrometry (IMS), which already produced breathtaking results [23, 28, 53]. In 2012 we have conducted the first mass measurement aiming at neutron-rich $^{84}$Kr projectile fragments, the analysis of experimental data is currently in progress.

The resolving power is not constant over the time-of-flight spectrum, see Figure 2 (b). In order to improve this, two time-of-flight detectors are being installed in the straight section opposite to the electron cooler of CSRe, see Figure 1 (left). These two detectors will enable in-ring velocity measurement of each stored ion, which in turn will be used to correct for the non-isochronicity conditions (for more details see Ref. [54]).

A complementary mass measurements technique, the Schottky Mass Spectrometry [34, 55, 56, 57] is being commissioned at CSRe. A new resonant Schottky pick-up [58, 59], which shall enable non-destructive frequency as well as intensity measurements of stored ions, has been installed in CSRe. This detector has a broad dynamic range being capable of measuring frequencies of single stored ions as well as high intensity beams of several mA. The intensity measurements will enable in-ring decay measurements [57, 60, 61].

Last but not least, the new developments at CSRe are used to achieve the optimal design the new-generation radioactive beam facility in China, which is being proposed now. A dedicated storage ring complex for mass measurements of very short-lived rare isotopes is envisioned there.

Acknowledgments
This work is supported in part by the 973 Program of China (No. 2013CB834401), the NSFC grants 10925526, 11035007, 10675147, 10805059, 11135005, 11075103, the Chinese Academy of Sciences, and BMBF grant in the framework of the Internationale Zusammenarbeit in Bildung und Forschung Projekt-Nr. 01DO12012. Y.A.L is supported by CAS visiting professorship for senior international scientists (Grant No. 2009J2-23). S.T. and K.B. acknowledge support by the Nuclear Astrophysics Virtual Institute (NAVI) of the Helmholtz Association. K.B. and Y.A.L. thank ESF for support within the EuroGENESIS program. B.A.B acknowledges support by NSF grant PHY-1068217, Michigan State University High Performance Computing Center and the Institute for Cyber-Enabled Research. T.Y. acknowledges support by The Mitsubishi Foundation.

References
[1] Wigner E P 1957 Proc. of the R A Welch Foundation Conf. on Chemical Research vol 1, ed W O Millikan (Houston: R A Welch Foundation)
[2] Weinberg S & Treiman S B 1959 Phys. Rev. 116 465–8
[3] Benenson W & Kashy E 1979 Rev. Mod. Phys. 51 527–40
[4] Britz J, Fage A & Antony M 1998 At. Data Nucl. Data Tables 69 125–59
[5] M. Mukherjee et al 2008 Eur. Phys. J. A 35 1–29
6 Dilling J et al 2003 Nucl. Instr. Meth. B 204 492–6
7 Kolhinen V S et al 2004 Nucl. Instr. Meth. A 528 776–87
8 Bollen G et al 2004 Nucl. Instr. Meth. A 532 203–9
9 Brodeur M et al 2012 Phys. Rev. Lett. 108 212501
10 Charity R J et al 2011 Phys. Rev. C 84 051308(R)
11 Herfurth F et al 2001 Phys. Rev. Lett. 87 142501
12 Pyle M C et al 2002 Phys. Rev. Lett. 88 122501
13 Ringle R et al 2007 Phys. Rev. C 75 055503
14 Yazidjian C et al 2007 Phys. Rev. C 76 024308
15 Saastamoinen A et al 2009 Phys. Rev. C 80 044330
16 Kankainen A et al 2010 Phys. Rev. C 82 052501(R)
17 Blaum K et al 2003 Phys. Rev. Lett. 91 260801
18 Triambak S et al 2006 Phys. Rev. C 73 054313
19 Kwiatkowski A A et al 2009 Phys. Rev. C 80 051302(R)
20 Signoracci A & Brown B A 2011 Phys. Rev. C 84 031301(R)
21 Henley E M & Lacy C E 1969 Phys. Rev. 184 1228–9
22 Bertsch G & Kahana S 1970 Phys. Lett. B 33 193–4
23 Zhang Y H et al 2012 Phys. Rev. Lett. 109 102501
24 Parikh A, Jose J, Ilaidis C, Moreno F & Rauscher T 2009 Phys. Rev. C 79 045802
25 Weber C et al 2008 Phys. Rev. C 78 054310
26 Breitenfeldt M et al 2009 Phys. Rev. C 80 035805
27 Haettner E et al 2011 Phys. Rev. Lett. 106 122501
28 Tu X L et al 2011 Phys. Rev. Lett. 106 112501
29 Herfurth F et al 2011 Eur. Phys. J. A 47 75
30 Zhan W L et al. 2010 Nucl. Phys. A 834 694c–700c
31 Xia J W et al 2002 Nucl. Instr. Meth. A 488 11–25
32 Hausmann M et al 2000 Nucl. Instr. Meth. A 446 569–80
33 Hausmann M et al 2001 Hyperfine Interactions 132 289–95
34 Franzke B, Geissel H & Münnzenberg G 2008 Mass Spectrometry Reviews 27 428–69
35 Litvinov Yu A et al 2010 Acta Physica Polonica B 41 511–23
36 Xu H et al 2009 Chinese Science Bulletin 54 4749–52
37 Wang M et al 2009 Int. J. Mod. Phys. E 18 352–8
38 Yan X L et al in preparation
39 Mei B et al 2010 Nucl. Instr. Meth. A 624 109–13
40 Tu X L et al 2011 Nucl. Instr. Meth. A 654 213–8
41 Sun B H et al 2009 Chinese Physics C 33 (Suppl. I) 161–3
42 Audi G, Wapstra A H & Thibault C 2003 Nucl. Phys. A 729 337–676
43 Audi G et al http://amdc.in2p3.fr/maastables/Ame2011int/filel.html
44 Hoischen R et al 2011 J. Phys. G 38 035104
45 Stadlmayr J et al 2004 Phys. Lett. B 586 27–33
46 Antony M S, Pape A & Britz J 1997 At. Data Nucl. Data Tables 66 1–63
47 Dossat C et al. 2007 Nucl. Phys. A A792 18–86
48 Brown B A & Sherr R 1979 Nucl. Phys. A 322 61–91
49 Honma M, Otsuka T, Brown B A & Mizusaki T 2002 Phys. Rev. C 65 061301(R)
50 Honma M, Otsuka T, Brown B A & Mizusaki T 2004 Rev. Rev. C 69 034335
51 Honma M, Otsuka T, Brown B A & Mizusaki T 2005 Eur. Phys. J. A 25 499–502
52 Ormand W E & Brown B A 1989 Nucl. Phys. A 491 1–23
53 Walker P M 2011 Nature Physics 7 281–2
54 Geissel H & Litvinov Yu A 2005 J. Phys. G 31 S1779–83
55 Radon T et al 2000 Nucl. Phys. A 677 75–99
56 Litvinov Yu A et al 2005 Nucl. Phys. A 756 3–38
57 Litvinov Yu A & Bosch F 2011 Rep. Prog. Phys. 74 016301
58 Nolden F et al 2011 Nucl. Instr. Meth. A 659 69–77
59 Zang Y D et al 2011 Chinese Physics C 35 1124–9
60 Winckler N et al 2009 Phys. Lett. B 679 36–40
61 Atanasov D et al 2012 Eur. Phys. J. A 48 22