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Revalidation of the isobaric multiplet mass equation at $A = 53$, $T = 3/2$

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ABSTRACT

The $T = 3/2$ isobaric analog state (IAS) in ^{53}Co is firmly established through a comprehensive measurement of β-delayed γ and proton decay of ^{53}Ni. The determined excitation energy of ^{53}Co IAS combined with the mass of ^{53}Co generates a precise mass excess of $-38\,333.6(27)$ keV for the ^{53}Co IAS, which is 70(18) keV lower than the previously adopted value. The new result solves a problem raised by incorrect assignments of the ^{53}Co IAS of unexpected deviation from the isobaric multiplet mass equation (IMME) at $A = 53$, $T = 3/2$.

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Isospin T is a quantum number introduced by Heisenberg to describe the charge independence of the nuclear force [1]. Within the isospin formalism, the proton and neutron belong to a $T = 1/2$ doublet with projections $T_z(n) = 1/2$ and $T_z(p) = -1/2$. States in isobaric nuclei with the same T and spin-parity J^π form a $2T + 1$ isobaric multiplet. The members of an isobaric multiplet, which are called isobaric analog states (IAS), have different projections $T_z = (N - Z)/2$, where N is the number of neutrons and Z the number of protons. Under the assumption that first order perturbation theory is sufficient to describe charge-dependent effects, the mass excesses (ME) of the members of an isobaric multiplet can be written in a quadratic form [2,3].

$$\mathrm{ME}(\alpha, T, T_z) = a(\alpha, T) + b(\alpha, T)T_z + c(\alpha, T)T_z^2, \tag{1}$$

where the a, b, c are coefficients depending on $\alpha = (A, J^\pi, \ldots)$ and the total isospin T, and A is the nuclear mass number. This relation is known as the isobaric multiplet mass equation (IMME).

The IMME is frequently tested using experimentally determined masses and, with the knowledge of at least four masses, it can be studied for the presence of higher order terms [4–16]. Theoretical works show that if first order perturbation theory does not suffice, higher order effects would be first absorbed within the a, b, and c-coefficients but a non-zero cubic term dT_z^3 of the order of 1 keV may remain [17–19]. Early reviews and compilations of data can be found in Refs. [20,21]. Recently, a first full evaluation of IAS [22–24] and extracted IMME coefficients [25] have highlighted significant deviations in the quadratic IMME for quartets and quintuplets in $A = 8$, 9, 32, 35, and 53 isobars. The last one with a non-zero d-coefficient of 39(11) keV [15] is noticeable because it is the first breakdown of IMME found in the fp-shell. However, this deviation is an open question due to the greater inherent ex-

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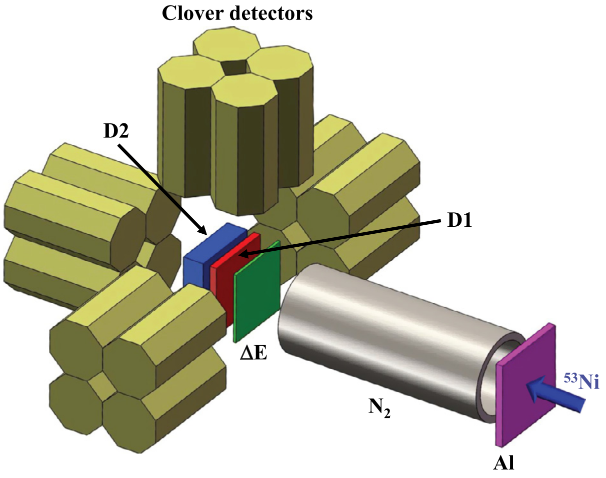

Fig. 1. (Color online.) Schematic of detection setup.

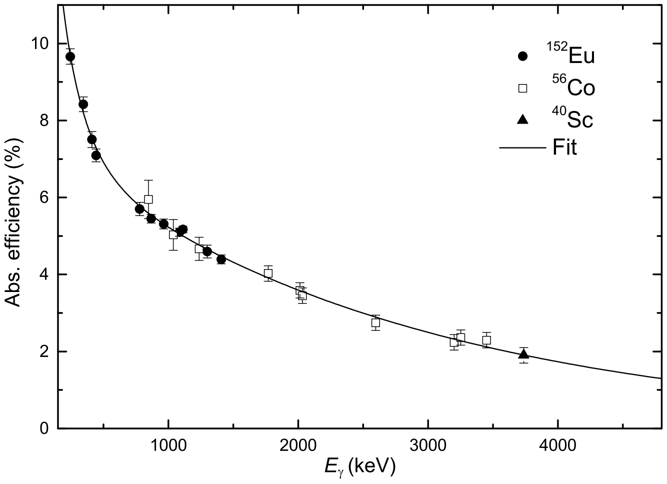

Fig. 2. The absolute efficiency of the clover detectors calibrated.

perimental uncertainty in the identification of the $T = 3/2$ IAS in ^{53}Co (^{53}Co^i, hereafter, as in [22,23,25]).

The previously adopted mass of ^{53}Co^i was determined by two measurements of β-delayed proton emission of ^{53}Ni [26,27]. In the first work, a proton group located at 1940(50) keV was identified and supposed to be the β-delayed proton of ^{53}Ni via ^{53}Co^i without specific evidence. In the recent work [27], the proton peak at 1929(18) keV was confirmed to be the strongest β-delayed proton of ^{53}Ni by a coincidence measurement. However, the branching ratio of this proton group is only 5.4(4)% [27], considerably lower than the estimation of ~63% for the super-allowed β decay from ^{53}Ni to ^{53}Co^i at that energy. This reveals that the decay of ^{53}Co^i is not dominated by the proton emission but dominated by the γ deexcitation to its ground state, which may be due to that the proton emission from $T = 3/2$ ^{53}Co^i to $T = 0$ states in ^{52}Fe is isospin forbidden and thus greatly suppressed. Unfortunately, the γ deexcitation of ^{53}Co^i was not detected in both previous works [26,27], thus the previous identification of ^{53}Co^i only based on the strongest β-delayed proton of ^{53}Ni is unconfirmed and needs to be checked by a new comprehensive measurement of ^{53}Ni decay including γ detection. Moreover, in a recent new measurement of ^{56}Zn β decay [28], the γ detection played a key role in the determination of the decay scheme and strongly indicated the limitation of measurement only with proton detection.

We have already touched on this issue in our previous work [29], but did not arrived at a definite conclusion due to the low statistics. In this letter we report a measurement of the β-delayed γ deexcitation and proton emission of ^{53}Ni. Contrary to the assignments in Refs. [26,27], our result shows that the main proton peak is not emitted from ^{53}Co^i. In fact, we found that the ^{53}Co^i decay is dominated by γ deexcitation. A new and more precise excitation energy of ^{53}Co^i is determined, leading to an improved IAS mass excess. With the new result, the cubic fit of IMME for the $A = 53$ quartet returns a d-coefficient compatible with zero, and so reaffirms the quadratic nature of the IMME in the fp-shell.

The experiment was performed at the HIRFL-RIBLL facility [30]. A ^{58}Ni^{25+} primary beam with an intensity of 30 enA and an energy of 68.3 MeV/u was fragmented on a 503 μm thick Be target. The ^{53}Ni fragments were separated and focused by RIBLL and implanted into a double-sided silicon strip detector (DSSSD) with 16 × 16 strips and a thickness of 500 μm (D1), see Fig. 1. Aluminum and nitrogen gas degraders were set upstream to adjust the implantation profile of the fragments in D1. Another DSSSD (D2) with a thickness of 1500 μm was installed downstream to measure the penetrating light particles.

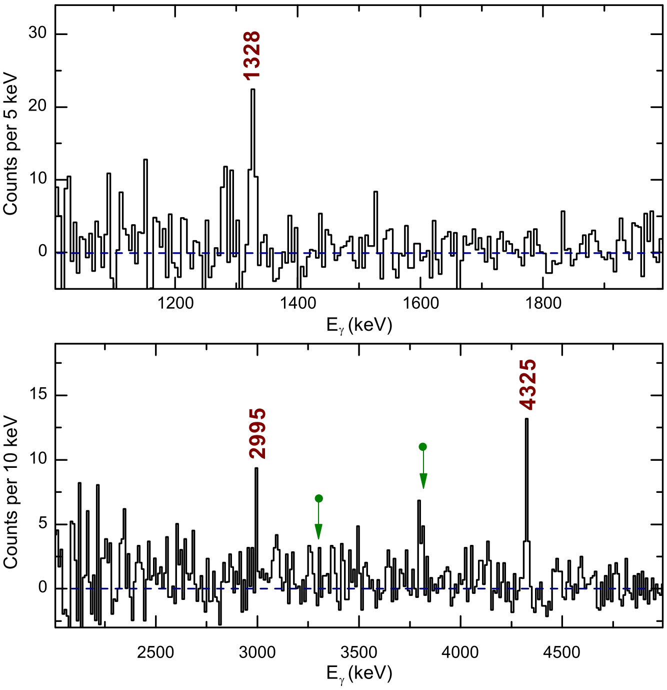

Fig. 3. (Color online.) β-Delayed γ spectra of ^{53}Ni. The backgrounds, attributed to random coincidence, have been subtracted. Three γ transitions mentioned in text are indicated. Positions of the single and double escape peaks of the 4325 keV γ-ray are marked by arrows.

The data analysis process is similar to that described in Ref. [29]. The total number of implanted ^{53}Ni nuclei was 1×10^4. The half-life of ^{53}Ni is determined to be 57(3) ms, in good agreement with previously reported values of 45(15) ms [26], 55.2(7) ms [27], and 56(8) ms [29].

Four segmented clover germanium detectors were placed around D1 to detect the β-delayed γ rays. The absolute efficiency of the clover detectors was calibrated by a standard ^{152}Eu source with known activities, a ^{56}Co source, and a β-delayed γ ray from the decay of ^{40}Sc with an energy of 3735.6(8) keV [31]. The experimental efficiency data points and a fitting curve are shown in Fig. 2.

Figure 3 shows the β-delayed γ spectra collected within three half-life windows (165 ms) after the ^{53}Ni implant, in which the random background taken from the area with decay-time larger

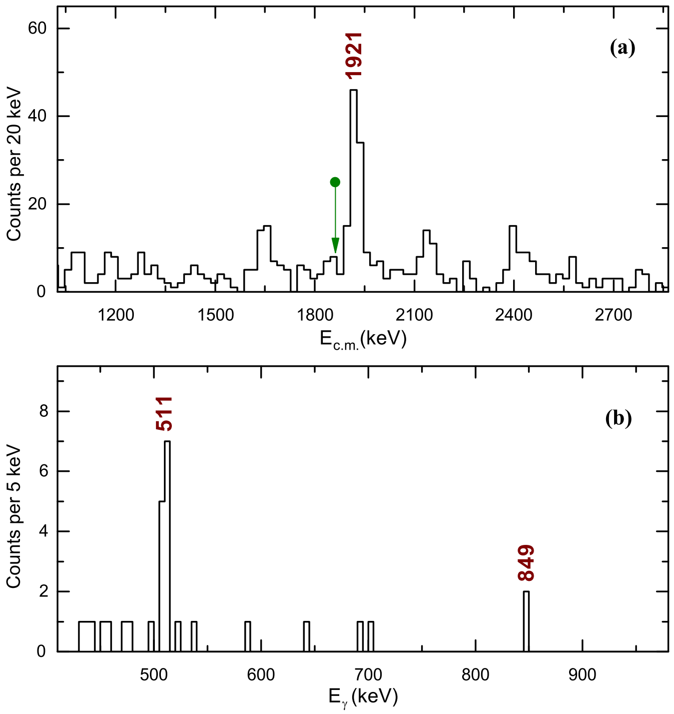

Fig. 4. (Color online.) (a) β-Delayed proton spectrum of ^{53}Ni. Position of the proton emitted from ^{53}Co^i to the first excited state in ^{52}Fe is marked by an arrow. (b) Gamma-ray spectrum gated by the 1921 keV proton peak.

than 1000 ms has been subtracted. Two γ transitions at 4325(2) and 2995(4) keV with relative intensities of 100% and 28%, respectively, are observed for the first time. The 1328(1) keV γ ray with a relative intensity of 71% is the known $9/2^- \to 7/2^-$ transition to the ground state [32]. According to the energy relation, the 2995 keV and parts of the 1328 keV γ rays are proposed to be in cascade, in parallel with the 4325 keV γ transition. Therefore, the two newly observed γ lines are assigned to be emitted from a state at 4325(2) keV in ^{53}Co. By normalizing the number of γ rays to that of measured β decay events, the absolute branching ratios of the 4325, 2995, and 1328 keV γ decays are determined to be 39(10)%, 11(4)%, and 28(7)%, respectively. As a result, the branching ratios of β-delayed γ emission via the 4325 keV state and the 1328 keV state in ^{53}Co are derived to be 50(11)% and 17(8)%, respectively.

Figure 4(a) shows the β-delayed proton spectrum of ^{53}Ni. In order to improve the proton energy resolution affected by the summing with the coincident β particles, we adopted a coincidence method similar to that previously described [33]. ^{53}Ni ions were implanted at the edge of D1 facing D2 and βp events were selected in coincidence with backward emitted β particles detected in D2. With these improvements, the proton energy resolution is 50 keV at FWHM. The absolute proton energy calibration was performed by measuring known β-delayed proton peaks of ^{41}Ti [34–37,27].

The total β-delayed proton branching ratio of ^{53}Ni decay is determined to be 22(1)%. The energy and branching ratio of the main proton peak are determined to be 1921(8) keV and 5.8(7)%, in good agreement with previous values [27]. Fig. 4(b) shows the γ spectrum gated by the 1921 keV proton peak and in which γ rays at 849 keV corresponding to the deexcitation of the first excited state in ^{52}Fe are observed. According to the proton-γ coincidence and the proton separation energy $S_p = 1615(7)$ keV of ^{53}Co [24], the main proton peak is emitted from a 4385(11) keV state in ^{53}Co.

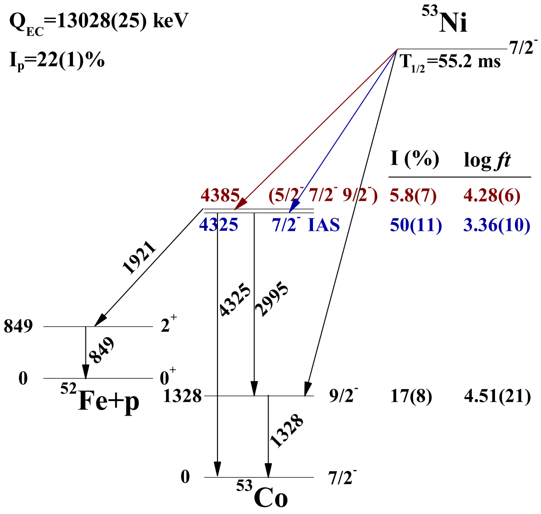

Fig. 5. (Color online.) Partial decay scheme of ^{53}Ni deduced from the present experiment.

For the 4325 keV state in ^{53}Co determined by γ deexcitation, the proton emission is expected to be visible since it is much higher than the S_p. However, no visible peak is found at 2710 keV in the proton spectrum shown in Fig. 4(a), which may be due to the significantly high l value for the proton emission from β-feeding states ($5/2^-$, $7/2^-$, $9/2^-$) in ^{53}Co to the ground state (0^+) in ^{52}Fe. Assuming that the 4325 keV state in ^{53}Co emits the proton to the first excited state (2^+) in ^{52}Fe, the corresponding proton energy would be 1861(7) keV, which is marked by an arrow in the Fig. 4(a). There seems to be a weak peak near the arrow but not very visible due to the limited statistics. Thus an upper limit of 0.9(3)% is recommended for the branching ratio of the proton decay of the 4325 keV state in ^{53}Co, which is negligible compared to that of γ deexcitation.

These experimental results lead to the partial decay scheme of ^{53}Ni summarized in Fig. 5. The $\log ft$ values are deduced using the excitation energies and branching ratios (I) from the present work, along with the experimental half-life [27] and ^{53}Ni Q_{EC} [24]. The small $\log ft$ of 3.36(10) confirms the super-allowed Fermi β decay to the 4325 keV state in ^{53}Co. The corresponding decay strength B is deduced to be 2.7(6) using $B = 6146/ft$ [38], in agreement with the model-independent theoretical super-allowed Fermi β decay strength $B(F) = (T - T_z)(T + T_z + 1) = 3$. Thus the 4325 keV state is unambiguously assigned as ^{53}Co^i. The $\log ft$ of ^{53}Ni β decay to the 1328 keV state and the 4385 keV state in ^{53}Co are estimated to be 4.51(21) and 4.28(6), respectively, which are within the normal range of a Gamow–Teller (GT) transition. The 60(11) keV energy difference between the 4385 keV state and ^{53}Co^i clearly shows that the assignments of ^{53}Co^i decay in Refs. [26,27] are incorrect.

We preformed large-scale shell-model calculations using GXPF1A [39,40] Hamiltonian, the two-body Coulomb interaction, and isovector single-particle energies [41], with a proper scaling factor $\sim\sqrt{\hbar\omega_A}$. The $\hbar\omega_A$ used is deduced from experimental data according to the procedure described in Ref. [42]. The calculation was carried out using NuShellX@MSU code [43]. The theoretical ^{53}Co^i is found to be the 10th $7/2^-$ state with an excitation energy of 4143 keV. The β decay from ^{53}Ni to ^{53}Co^i is found to be dominated by the Fermi transition. The GT and the Fermi strength of the super-allowed β decay are calculated to be 0.12 (with quenching factor $q_F = 0.74$) and 2.98, respectively, leading to a $\log ft = 3.30$, and the corresponding branching ratio is 57.6% at the excitation energy of 4325 keV, which agrees well with the experimental result.

Table 1
The theoretical electromagnetic transition (upper part) and the proton decay (lower part) properties of ^{53}Co^i compared with experimental results.

Decay mode	J^{π}_{f}	$E^{exp}_{c.m.}$ (keV)	Γ_{theory} (eV)	I_{theory} (%)	I_{exp} (%)
$\beta\gamma$	$7/2^-_{g.s.}$ in ^{53}Co	4325	0.21	31.1	39(10)
	$9/2^-_{1328}$ in ^{53}Co	2995	0.11	16.3	11(4)
	Sum of the others	–	0.04	5.3	–
	Total	–	0.36	52.7	50(11)
βp	$0^+_{g.s.}$ in ^{52}Fe	2710	0.003	0.4	–
	2^+_{849} in ^{52}Fe	1861	0.03	4.4	< 0.9
	Total	–	0.033	4.8	<0.9

Table 2
The isospin mixing of ^{53}Co^i state with $7/2^-$, $T = 1/2$ states in the range of ±500 keV.

$E_x - E_{IAS}$ (keV)	$B(F)$	Isospin mixing (%)
−446	2.68×10^{-4}	0.01
−313	2.15×10^{-5}	0.00
−134	4.27×10^{-3}	0.14
43	7.65×10^{-3}	0.26
216	4.99×10^{-4}	0.02
407	1.93×10^{-5}	0.00
482	4.35×10^{-5}	0.00

Table 1 shows theoretical decay properties of ^{53}Co^i. The branching ratio of β-delayed γ deexcitation is deduced from the sum of $B(E2)$ and $B(M1)$ values. The $B(E2)$ values were calculated using standard values for effective charges, $e_p = 1.5e$, $e_n = 0.5e$, while $B(M1)$ values were obtained with effective spin g-factors, corresponding to $q_F = 0.74$, i.e. $g^s_p = 4.134$, $g^s_n = -2.831$ and $g^l_p = 1$, $g^l_n = 0$. The two considered transitions, to the ground and the 1328 keV, $9/2^-$ state, respectively, provide the major contribution in the deexcitation of ^{53}Co^i. The calculated branching ratios of them are 31.1% and 16.3%, respectively, in good agreement with our measurement. The proton decay widths were calculated as $\Gamma_p = \sum_{nlj} C^2 S(nlj)\Gamma_{sp}(nlj)$ [44], where $C^2 S(nlj)$ is the spectroscopic factor and $\Gamma_{sp}(nlj)$ the single-proton width for an emission of a proton from a (nlj) quantum orbital. The single-particle widths were obtained from scattering cross sections calculated with a Woods–Saxon potential [45,46]. The calculated total branching ratio of the proton decay (4.8%), although larger than the experimental value, is significantly smaller than that of the γ decay.

The comparison between theoretical calculation and experimental data reveals an abnormal hindrance of the proton emission of ^{53}Co^i, which caused the incorrect identification of ^{53}Co^i in previous works [26,27]. According to the shell-model calculation, this hindrance is due to small isospin impurity in ^{53}Co^i caused by isospin mixing with $7/2^-$, $T = 1/2$ states, as summarized in Table 2 using two-level mixing relationship [47].

The excitation energy of ^{53}Co^i obtained in the present work together with the AME12 mass excess of ^{53}Co [24] results in a more precise mass excess of −38 333.6(27) keV for ^{53}Co^i, which is 70(18) keV lower than the adopted value of −38 264(18) keV in the latest evaluation [25] and as expected for a quadratic IMME form [48]. The result, together with mass excesses of other members in the $A = 53$ quartet taken from Ref. [25], is used for the IMME test, as listed in Table 3.

Table 3
IMME coefficients extracted for the $A = 53$, $T = 3/2$ quartet. Mass excesses are taken from Ref. [25], except for that of ^{53}Co^i obtained in the present work.

Nucl.	T_z	ME (keV)	a, b, c (keV)	a, b, c, d (keV)
^{53}Mn	3/2	−54 689.0(6)	$a = -42\,561.2(25)$	$a = -42\,559.7(28)$
^{53}Fe^i	1/2	−46 697(3)	$b = -8361.4(37)$	$b = -8364.7(47)$
^{53}Co^i	−1/2	−38 333.6(27)	$c = 184.1(30)$	$c = 177.7(63)$
^{53}Ni	−3/2	−29 631(25)	$\chi^2/n = 1.34$	$d = 5.4(46)$

The cubic fit returns a coefficient $d = 5.4(46)$ keV, compatible with zero within a 2σ experimental error, and allows us to conclude that previous deviation is the direct consequence of experimental accuracy in the ^{53}Co^i identification, as expected in Refs. [15,48]. The quadratic fit returns a normalized chi-square $\chi^2/n = 1.34$ with $n = 1$ in our case. The a, b, and c-coefficients change very little in accommodating the d-term ($\Delta a = +1.5$, $\Delta b = -3.3$, $\Delta c = -6.4$ keV), in agreement with the expectation of that d-coefficient is a correcting term [17]. Furthermore, the major shifts are in the b and c-coefficients, as predicted in Ref. [17]. Since the precision of the ^{53}Co^i mass has improved significantly, the uncertainty of the IMME test for the $A = 53$ quartet mainly comes from the determination of the mass of ^{53}Ni [15]. In order to search for higher order IMME contributions, further studies of ^{53}Ni mass with improved resolution are highly desirable.

Furthermore, the incorrect assignments in previous works [26,27] indicate the ambiguities of IAS identified only via β-delayed proton measurements. It is expected that a similar situation exists in the $A = 52$ quintuplet [25,48], another significant deviation of the IMME in the fp-shell, in which the mass of the $T = 2$ IAS in ^{52}Co is also determined from a β-delayed proton emission of ^{52}Ni with a low branching ratio [27].

In summary, the lowest $T = 3/2$ state in ^{53}Co has been established via the measurement of the β-delayed γ deexcitation of ^{53}Ni. The new mass excess of ^{53}Co^i deduced with an improved precision is 70(18) keV lower than the previously adopted value. The cubic fit based on current results returns a d-coefficient compatible with zero, and so restores the validity of the IMME in quadratic form for the $A = 53$ quartet. This underlines the necessity of γ detectors in the IAS identification, and also raises questions concerning IAS identification in previous measurements of βp decay with low branching ratio.

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