Isospin Mixing between Low-Lying States of the Odd-Odd $N = Z$ Nucleus ^{54}Co

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Isospin mixing of the recently discovered doublet of 4^+ states with isospin quantum numbers $T = 0$ and $T = 1$ in ^{54}Co is analyzed. It is shown that the measured $E2/M1$ multipole mixing ratios can be used to estimate the isospin mixing of these states. Combining the new experimental data with results of a shell model calculation, the amount of isospin mixing is found to be $\approx 0.2\%$.

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Isospin is a fundamental concept of hadron physics. It was introduced [1] in nuclear physics because of the (approximate) charge independence of nuclear forces and has been an important tool for the classification of nuclear and hadronic states ever since. Nuclear forces favor in general the states of the lowest possible isospin quantum number, $T = |T_z| = |N - Z|/2$. In odd-odd $N = Z$ nuclei this tendency towards $T = |T_z|$ is weakened and states with $T = T_z + 1 = 1$ compete strongly with the lowest $T = T_z = 0$ states leading there in many cases to a $J^\pi = 0^+, T = 1$ ground state. Charge independence is an approximate symmetry only and the isospin quantum numbers, T, are consequently slightly mixed in reality. Isospin mixing can be attributed in nuclear physics to the perturbation caused by the Coulomb interaction, by the proton-neutron mass difference, and by charge-dependent parts of the nuclear force.

There is currently great interest in the measurement of the size of isospin mixing in heavy nuclei. It is expected in different nuclear models [2–4] to rapidly increase with nuclear mass along the $N = Z$ line until reaching a value of 4–5% in the ground state of ^{100}Sn. This interest has recently even intensified because of the impact of our understanding of nuclear isospin mixing on a unitarity test of the Cabibbo-Kobayashi-Maskawa (CKM) matrix. Super-allowed Fermi β decay ($\Delta T = 0$, $\Delta S = 0$) rates can be used to extract the entry, V_{ud}, of the CKM matrix with a very high precision. Available data [5,6] suggest that the CKM-matrix fails the unitarity test pointing to physics beyond the standard model. These conclusions partly depend on corrections for nuclear isospin mixing which must be calculated with nuclear theory for heavy $N = Z$ nuclei. In view of the present debate, e.g., [7], it is preferable to directly determine the size of isospin mixing from experiment.

A well-known way for a determination of isospin mixing in low-energy nuclear states is the precise measurement of the rates for isospin-forbidden transitions; that is, because such transition rates are sensitive to small admixtures to the wave functions that make the decays possible. For instance, analyzing an isospin-forbidden $E1$ decay, Ennis *et al.* [8,9] studied the isospin purity of low-energy $T = 0$ states of the $N = Z$ nucleus ^{64}Ge with spin and parity $J_i^\pi = 4_1^+$ and 5_1^-. Another isospin forbidden $E1$ decay has just been identified in the odd-odd $N = Z$ nucleus ^{46}V [10,11]. The estimate of isospin mixing using $E1$ decays is, however, hampered by difficulties with reliable calculations of $E1$ transition rates.

$M1$ transition rates can also provide information on the isospin mixing [12,13]. Although, the isoscalar ($\Delta T = 0$) $M1$ transitions are not strictly forbidden, they are strongly hindered in comparison to the isovector ($\Delta T = 1$) $M1$ transitions. In the case of strong isovector $M1$ transitions between some states of odd-odd $N = Z$ nuclei [14], the degree of hindrance of isoscalar $M1$ transitions is very high and is comparable to the one for the isospin-forbidden $\Delta T = 0$ $E1$ transitions. But the precise measurement of strongly hindered decay rates between low-energy states is often limited to low-mass nuclei where the Coulomb effects are small. It is, therefore, of general interest to find an alternative for the measurement of the isospin mixing, particularly, in heavy nuclei at the $N = Z$ line.

It is the purpose of this Letter to demonstrate that the measurement of $E2/M1$ multipole mixing ratios of γ transitions between excited states of heavy odd-odd $N = Z$ nuclei can be used as a source of information on the isospin mixing between basis states of a chosen configurational space of valence nucleons.

We will use below the recent measurement [15,16] of the $E2/M1$ multipole mixing ratios, δ, of the $4_{1,2}^+ \rightarrow 3_1^+$ transitions in the odd-odd $N = Z$ nucleus ^{54}Co for the determination of the isospin mixing in this 4^+ doublet. In doing so we need, besides the measured values of δ, minimal and robust theoretical input, namely, the far dominance of allowed isovector over isoscalar $M1$ matrix elements and the robust determination of isoscalar $E2$ transition strengths calculated *before isospin mixing*. To be specific, we will use below the nuclear shell model (SM) with the schematic surface-δ interaction (SDI) and the effective FPD6 residual interaction [17], for example. Any other model, e.g., one of those used for the estimate of Coulomb correction factors for super-allowed Fermi decays, might be used instead.

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Low-spin states of the odd-odd $N = Z$ nucleus ^{54}Co were recently studied with the fusion evaporation reaction ^{54}Fe$(p, n\gamma)^{54}$Co at a proton beam energy $E_p = 15$ MeV [15,16] at the FN-Tandem accelerator of the University of Cologne. In-beam gamma-ray spectroscopy was performed, many new levels were identified, spin and parity quantum numbers, J^π, have been assigned, and several multipole mixing ratios, δ, of γ transitions were measured.

In particular, there exist two $J^\pi = 4^+$ states, that are separated by only 200 keV in energy, and both decay to the $T = 0$, 3_1^+ state by dominantly dipole transitions [see Fig. 1(A)]. The spin and parity quantum number assignments 4^+ for these levels at 2652 and 2852 keV have been done in Ref. [15,16]. From the comparison to the $T_z = 1$ isobaric partner nucleus ^{54}Fe, which has only one $J^\pi = 4^+$ state in this energy range, it is obvious that this doublet of 4^+ states in ^{54}Co must comprise one configuration with $T = 1$ and another with $T = 0$. From the far dominance of isovector over isoscalar $M1$ transitions in $N = Z$ nuclei one must expect the smallest $E2/M1$ mixing ratio of the $4^+ \to 3^+$ transitions for the 4^+ state with dominant $T = 1$ component. Indeed, shell model calculations discussed below predict that this multipole mixing ratio would either be $\delta = 1.31$ or $\delta = 0.009$ for pure isoscalar (IS; $\Delta T = 0$) or pure isovector (IV; $\Delta T = 1$) transitions, respectively.

The $J^\pi = 4_1^+$ state at 2652 keV decays by a pure $M1$ transition to the $T = 0$, 3_1^+ state at 1822 keV with an $E2/M1$ multipole mixing ratio $\delta(4_1^+ \to 3^+) = 0.00(3)$. The strongest decay channel of the 4_2^+ level at 2852 keV is to the $T = 0$, 3_1^+ state with 66(2)% of the total intensity and shows a mixed $E2/M1$ character. The $E2/M1$ multipole mixing ratio of this transition was determined to be $\delta_{\rm expt} = 0.12(4)$ [16] corresponding to 98.6(9)% of $M1$ radiation and 1.4(9)% of $E2$ radiation. The vanishing $\delta(4_1^+ \to 3^+)$ value indicates that the 4_1^+ state has dominantly $T = 1$ character leaving the dominant $T = 0$ character to the 4_2^+ state. The second mixing ratio, $\delta_{\rm expt}(4_2^+ \to 3^+)$ is finite but smaller than expected in the case of pure isospin. Therefore, it is sensitive to the size of the isospin mixing between the 4^+ configurations with isospin quantum numbers $T = 0$ and $T = 1$.

To estimate the size of the isospin admixture $P_{4_2^+}(T = 1)$ of the $4^+, T = 1$ component in the observed 4_2^+ state with dominant $T = 0$ character, we employ a two state mixing analysis. We assume that both observed 4_1^+ and 4_2^+ states are the mixtures of the calculated $T = 0$, $J = 4^+$ and $T = 1$, $J = 4^+$ configurations:

$$\begin{aligned} |4^+_{1,\rm expt}\rangle &= \sqrt{1-b^2}\,|4^+_{T=1,\rm calc}\rangle - b\,|4^+_{T=0,\rm calc}\rangle, \\ |4^+_{2,\rm expt}\rangle &= \sqrt{1-b^2}\,|4^+_{T=0,\rm calc}\rangle + b\,|4^+_{T=1,\rm calc}\rangle, \end{aligned} \quad (1)$$

while the low-lying $T = 0$, 3^+ state is assumed to contain no admixtures with $T = 1$ because a corresponding state is missing in the $T = 1$ isobaric partner nuclei. The square of the isospin mixing amplitude, b, represents the isospin impurity for the discussed state, $P_{4_2^+}(T = 1) = b^2$. In order to determine the amplitude b we use the measured multipole mixing ratio of the $4_2^+ \to 3_1^+$ transition:

$$\begin{aligned} \delta_{\rm expt}(4_2^+ \to 3_1^+) &\equiv \delta_{\rm expt} \\ &= C(E_\gamma) \cdot \frac{\langle 4^+_{2,\rm expt} \parallel E2 \parallel 3^+_{1,\rm expt}\rangle}{\langle 4^+_{2,\rm expt} \parallel M1 \parallel 3^+_{1,\rm expt}\rangle}, \end{aligned} \quad (2)$$

where $C(E_\gamma) = 0.835 E_\gamma \cdot \frac{\mu_N}{eb\cdot \rm MeV}$ is a known factor. We use further the following short notations:

$$\begin{aligned} M1_{\rm IS}(J) &= \langle 4^+_{T=0,\rm calc} \parallel M1 \parallel J^+_{T=0,\rm calc}\rangle, \quad E2_{\rm IS}(J) = \langle 4^+_{T=0,\rm calc} \parallel E2 \parallel J^+_{T=0,\rm calc}\rangle, \\ M1_{\rm IV}(J) &= \langle 4^+_{T=1,\rm calc} \parallel M1 \parallel J^+_{T=0,\rm calc}\rangle, \quad E2_{\rm IV}(J) = \langle 4^+_{T=1,\rm calc} \parallel E2 \parallel J^+_{T=0,\rm calc}\rangle, \end{aligned} \quad (3)$$

$$\delta_{\rm IS}(J) = C(E_\gamma) E2_{\rm IS}(J)/M1_{\rm IS}(J) \quad \text{and} \quad \delta_{\rm IV}(J) = C(E_\gamma) E2_{\rm IV}(J)/M1_{\rm IV}(J), \quad (4)$$

where J denotes either the $T = 0$, 3_1^+, or 5_1^+ states. Using Eqs. (1)–(4) we obtain the following expression for the experimental mixing ratio:

$$\delta_{\rm expt} = C(E_\gamma) \cdot \frac{\sqrt{1-b^2} \cdot E2_{\rm IS}(3) + b \cdot E2_{\rm IV}(3)}{\sqrt{1-b^2} \cdot M1_{\rm IS}(3) + b \cdot M1_{\rm IV}(3)}. \quad (5)$$

Since $\sqrt{1-b^2} \approx 1$, Eq. (5) can be solved with respect to b and one obtains

$$b = -\frac{M1_{\rm IS}(3)}{M1_{\rm IV}(3)} \left[\frac{\delta_{\rm expt} - \delta_{\rm IS}(3)}{\delta_{\rm expt} - \delta_{\rm IV}(3)} \right]. \quad (6)$$

The isospin mixing can, therefore, be determined from the experimental mixing ratio and a reliable calculation of the electromagnetic matrix elements in Eq. (3).

In [15] the new data on ^{54}Co were compared to shell model calculations within the $(f_{7/2})^{14-k}(p_{3/2})^k$ configurational space [$k = k_n + k_p$, $0 \le k_{n(p)} \le 1$] with residual SDI. The calculations reproduce quite well the structure of the yrast states, that are shown to have the properties of quasideuteron states (see [14,15,18]). In this paper we extend the configurational space to $(f_{7/2})^{14-k}(p_{3/2})^{l_p+l_n}(f_{5/2})^{m_p+m_n}(p_{1/2})^{n_p+n_n}$ with $0 \le l_{n(p)}, m_{n(p)}, n_{n(p)}, k_{n(p)} \le 1$ and $k_{n(p)} = l_{n(p)} + m_{n(p)} + n_{n(p)}$. As in Ref. [15] we have used the SDI with a modified $f_{7/2}$ two-body matrix element for the $J^\pi = 7^+$ state. This modification enhances the monopole part of the residual interaction for the $f_{7/2}$ orbital and helps to lower the energy of the $J^\pi = 7^+$ state. This modification allows us to keep fixed the value of the single particle energy for the $p_{3/2}$ orbital ($\epsilon_{p_{3/2}} = 2.0$ MeV) without regard to which core is used, ^{40}Ca or ^{56}Ni. The values of single particle energies are 2.0 MeV, 4.0 MeV, and 5.5 MeV for the $p_{3/2}$, $p_{1/2}$, and $f_{5/2}$ orbitals, respectively. Inclusion of the $f_{5/2}$ and $p_{1/2}$ orbitals results only in minor changes of the structure of yrast states. The comparison of the data to

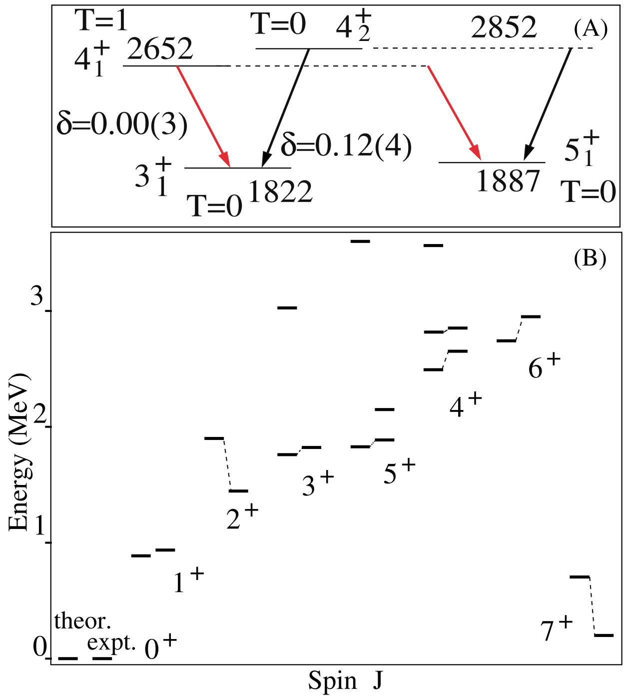

FIG. 1 (color online). (A) The decay scheme of the $4_1^+, T = 1$ and $4_2^+, T = 0$ states to the 3_1^+ and the 5_1^+ $T = 0$ states of ^{54}Co. (B) Comparison of the experimental and calculated low-energy spectra for ^{54}Co.

the shell model results for low-lying states is given in Fig. 1(B). The structure of the states of our particular interest is shown in Table I. The parameters of the residual SDI, $A_{pp}^{T=1} = A_{nn}^{T=1} = A_{pn}^{T=1} = 0.55$ MeV, were fitted to reproduce the low-energy level schemes of the neighboring nuclei. The SDI parameter $A_{pn}^{T=0} = 0.50$ MeV and the strength of the isospin-isospin interaction $(\tau_1 \cdot \tau_2)$ $B = 0.11$ MeV were obtained from the optimum reproduction of the spacing of $T = 0$ and $T = 1$ levels in ^{54}Co, respectively. Effective spin g factors were obtained from the measured magnetic moments of the "one-hole" nuclei, ^{55}Co and ^{47}Ca, respectively. Bare orbital g factors, $g_p^l(n) = 1(0)\mu_N$, were used. The effective proton charge, $e_p = 2.11e$, was obtained from a fit to the $B(E2; 2_1^+ \rightarrow 0_1^+)$ value in the isobaric partner nucleus ^{54}Fe. The sum of the proton and neutron effective charges, $e_p + e_n = 3.21\, e$, was finally obtained from the reproduction of the intensity branching ratio 0.104(4) [15] between the isoscalar $2_1^+ \rightarrow 0_1^+$ $E2$ transition and the isovector $2_1^+ \rightarrow 1_1^+$ $M1$ transition.

To check the sensitivity of the $M1$ and $E2$ transition matrix elements to the particular choice of the configurational space and residual interaction we performed another shell model calculation. We used the FPD6 residual interaction [17] in the $(f_{7/2})^{14-l-m}(p_{3/2})^l(p_{1/2})^m$ space with the following restrictions: $0 \leq l_{n(p)} \leq 2(l = l_p + l_n)$ and $0 \leq m_{n(p)} \leq 1$ $(m = m_p + m_n)$. Results of calculations for this case are included in Table II.

The two sets of calculations presented above show that the components of the wave functions, which determine the isovector $M1$ properties of the states, are robust, i.e., are largely insensitive to the particular choice of the configurational space and residual interaction (see Tables I and II). We note that the isoscalar $4^+ \rightarrow 5_1^+$ $E2$ transition is significantly stronger (a factor of 20–50) than the one to the 3_1^+ state. This is a generic feature for both calculations and originates probably from the angular momentum coupling of the considered many particle configurations. We stress that the calculation of these strong, allowed isovector $M1$ and isoscalar $E2$ transitions is stable against any reasonable changes in the Hamiltonian.

The calculated transition matrix elements and multipole mixing ratios are displayed in Table II. In particular, we observe that $\delta_{\mathrm{IV}}(3) \ll \delta_{\mathrm{expt}}$ because of the large isovector $M1$ matrix element. Therefore, we can further simplify Eq. (6) to

$$b \approx -\frac{M1_{\mathrm{IS}}(3)}{M1_{\mathrm{IV}}(3)}\left[1 - \frac{\delta_{\mathrm{IS}}(3)}{\delta_{\mathrm{expt}}}\right] = -\frac{M1_{\mathrm{IS}}(3)}{M1_{\mathrm{IV}}(3)} + \frac{C(E_\gamma)}{\delta_{\mathrm{expt}}}\frac{E2_{\mathrm{IS}}(3)}{M1_{\mathrm{IV}}(3)}, \tag{7}$$

which is a linear function of $M1_{\mathrm{IS}}(3)$ with a very small slope, $-1/M1_{\mathrm{IV}}(3)$ and the offset, $C(E_\gamma)/\delta_{\mathrm{expt}} \cdot E2_{\mathrm{IS}}(3)/M1_{\mathrm{IV}}(3)$. Since the slope as a function of $M1_{\mathrm{IS}}(3)$ is small, the mixing amplitude depends little on the details of $M1_{\mathrm{IS}}(3)$. In particular, for the case $\delta_{\mathrm{IS}}(3) \gg \delta_{\mathrm{expt}}$, which is appropriate for the situation in ^{54}Co, one finally obtains

$$b \approx \frac{C(E_\gamma)}{\delta_{\mathrm{expt}}}\frac{E2_{\mathrm{IS}}(3)}{M1_{\mathrm{IV}}(3)}, \tag{8}$$

Using the $M1$ and $E2$ matrix elements from the shell model calculation with SDI (upper half of Table II) and the corresponding experimental $E2/M1$ mixing ratio we obtain $P_{4_2^+}(T = 1) \approx 0.23_{-0.10}^{+0.29}\%$ for the size of the $T = 1$ admixture to the 4_2^+ state of the $J^\pi = 4^+$ doublet in ^{54}Co. The corresponding off-diagonal matrix element, $\langle V_{\mathrm{mix}}\rangle$, causing the mixing can be estimated to $\langle V_{\mathrm{mix}}\rangle \approx |b[E(4_2^+) - E(4_1^+)]| = 9.6_{-2.4}^{+4.8}$ keV. The calculation with the FPD6 interaction yields $P_{4_2^+}(T = 1) \approx 0.10_{-0.04}^{+0.13}\%$ and $\langle V_{\mathrm{mix}}\rangle = 6.3_{-1.5}^{+3.2}$ keV.

TABLE I. Calculated structure of some low-energy eigenstates of the considered shell model Hamiltonian with residual SDI and FPD6. The weights of the dominant configurations are shown.

	Component contributions to wave functions (%)					
	State, J_i^π, T_i					
	$3_1^+, T = 0$		$4_1^+, T = 1$		$4_2^+, T = 0$	
Component	SDI	FPD6	SDI	FPD6	SDI	FPD6
$(f_{7/2}^{-2})_J^T$	72	81	71	85	0	0
$[(f_{7/2})^{-3}(p_{3/2})^1]_J^T$	10	9	9	6	80	68
$[(f_{7/2})^{-4}(p_{3/2})^2]_J^T$	8	8	10	7	12	13
$[(f_{7/2})^{-3}(p_{1/2})^1]_J^T$	0.2	0.1	2	1	3	8

TABLE II. Calculated values of the $M1$ and $E2$ matrix elements in units of μ_N and eb $[(0.0348eb)^2 = 1$ W. u.], respectively, mixing ratios δ and branching ratio BR as defined in the text. The results of two calculations with SDI and FPD6 interactions are compared. Experimental values of mixing and branching ratios are given in columns labeled by "Expt." The extracted value of the isospin admixture, $P_{4_2^+}(T = 1)$, the corresponding isospin mixing matrix element, $\langle V_{\rm mix}\rangle$, and the spreading width, $\Gamma_\downarrow$, [19] are shown. The calculated value of BR taking into account the observed isospin mixing is shown in the column labeled by "Mix."

						δ			BR		$P_{4_2^+}(T=1)$	$\langle V_{\rm mix}\rangle$	$\Gamma_\downarrow$
Int.	J_i^π	J_f^π	ΔT	μ_N	eb	Th.	Expt.	Th.	Expt.	Mix.	%	keV	keV
SDI	4_2^+	3_1^+	IS	0.0214	0.0327	1.31	0.12(4)				$0.23^{+0.29}_{-0.10}$	$9.6^{+4.8}_{-2.4}$	$2.9^{+3.6}_{-1.3}$
	4_1^+	3_1^+	IV	−4.873	−0.0623	0.009	0.00(3)						
	4_2^+	5_1^+	IS	0.005	0.2412	38.8		24.9	0.51(3)	1.1(3)			
	4_1^+	5_1^+	IV	4.678	0.0702	0.01							
FPD6	4_2^+	3_1^+	IS	0.0101	0.0257	2.19	0.12(4)				$0.10^{+0.13}_{-0.04}$	$6.3^{+3.2}_{-1.5}$	$1.3^{+1.6}_{-0.5}$
	4_1^+	3_1^+	IV	−5.81	−0.0619	0.01	0.00(3)						
	4_2^+	5_1^+	IS	0.0025	0.1244	40.1		13.9	0.51(3)	0.9(1)			
	4_1^+	5_1^+	IV	5.82	0.0884	0.01							

These values agree with the above results within the uncertainties.

The $4_2^+, T = 0$ state, furthermore, decays to the $5_1^+, T = 0$ state [15] with a decay branching ratio $\mathrm{BR} = I_\gamma(4_2^+ \to 5_1^+)/I_\gamma(4_2^+ \to 3_1^+) = 0.51(3)$. Before taking the isospin mixing into account the shell model matrix elements (see Table II) would have resulted in a value of BR = 24.9 (BR = 13.9 for FPD6), about 2 orders of magnitude larger than the experimental value, because, as we have already noted above, the isoscalar $4_2^+ \to 5_1^+ E2$ matrix element is a factor of 8 larger than the corresponding $E2$ matrix element to the 3_1^+ state. After considering the small isospin admixture deduced above for the $4_2^+, T = 0$ state, we find that the decays of this state are dominated by the admixtures of the strong isovector $M1$ transitions with almost equal matrix elements to the $T = 0$ 3_1^+ and 5_1^+ states. Consequently, the theoretical prediction for the considered branching ratio is decreased to a value of BR = 1.1(3) [BR = 0.9(1) for FPD6] in agreement with experiment within a factor of 2. The given error originates in the uncertainty of the isospin mixing amplitude derived above. This branching ratio represents another observable which independently supports our conclusion about the size of isospin mixing in the $J^\pi = 4^+$ isospin doublet in ^{54}Co.

It is worth noting that there are other possibilities to estimate the effects caused by isospin nonconserving interactions in ^{54}Co. Using, for example, the hybrid model of Colo *et al.* [3] that exploits the energy-weighted sum rule for isovector monopole excitations, [see Eq. (11) in [3]] one can estimate that the isospin mixing for the ground state of ^{54}Co is ≈0.7%. Other calculations addressed instead of the isospin mixing directly the Coulomb correction, δ_C, for the interpretation of Fermi beta decays. Ormand and Brown reported [20] a Coulomb correction $\delta_C = 0.35(10)\%$ for the isobaric $0^+, T = 1$ analog states in ^{54}Co and ^{54}Fe. Our results represent new information on the isospin mixing for excited states in ^{54}Co which is complementary to the results mentioned above for ground state properties.

In conclusion, we have demonstrated that a precise measurement of the $E2/M1$ multipole mixing ratio of a dominantly isoscalar γ transition between bound states of a heavy odd-odd $N = Z$ nucleus can be used for the determination of the size of isospin mixing in comparison to model calculations. We estimated the size of isospin mixing between close-lying $J^\pi = 4^+$ states of the heavy odd-odd $N = Z$ nucleus ^{54}Co to be 0.23(8)% and the corresponding mixing matrix element $V_{\rm mix} \approx 10$ keV.

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