EXTREMELY SMALL ISOSPIN IMPURITY IN THE LOWEST $T = 2$ ISOBARIC ANALOGUE STATE IN ^{52}Co*

Xing Xu[a], Peng Shuai[a], Peng Zhang[a,b]
Yuhu Zhang[a], Meng Wang[a,†]

[a]Key Laboratory of High Precision Nuclear Spectroscopy
and Center for Nuclear Matter Science, Institute of Modern Physics
Chinese Academy of Sciences
Lanzhou 730000, People's Republic of China
[b]University of Chinese Academy of Sciences
Beijing 100049, People's Republic of China

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Combining our newly measured masses of ground and (2^+) isomeric states of ^{52}Co with previous measurements of ^{52}Ni β decay, a remarkably different decay scheme of ^{52}Ni is constructed. In the new scheme, the proton group with the highest intensity corresponds to the decay from the 1^+ excited state in ^{52}Co, and not from the $J^\pi = 0^+, T = 2$ isobaric analog state (IAS) as it was commonly assumed. This finding indicates that the degree of isospin impurity in the lowest $T = 2$ IAS in ^{52}Co is extremely small, thus leading to a negligibly weak proton emission from the IAS and a mistaken assignment. Effort to find an explanation for this phenomenon is highly called for.

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1. Introduction

Symmetries play an important role in understanding our physical world, reflecting invariances of a complex system. In nuclear physics, the isospin symmetry was introduced by Heisenberg [1] and developed by Wigner [2] based on the almost identical behaviour of protons and neutrons. The degeneracy of the two kinds of fermions represents the charge-independent nature of nuclear forces and was given by the invariance of the Hamiltonian of the strong interaction under the action of the SU(2) group [1, 3]. However, the

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† Corresponding author: wangm@impcas.ac.cn

electromagnetic interaction and the charge-dependent part of the nucleon–nucleon interaction, the latter being often called the isospin-non-conserving (INC) force, break the isospin symmetry, leading to the impurities in the wave functions of involved states.

Determining the degree of isospin impurity in nuclear states is not only an important theoretical question for understanding the role of isospin symmetry and its breaking in many-body systems, but it also has crucial consequences for studies of fundamental interactions [4] and nuclear astrophysics [5]. In particular, in order to probe the conserved vector current hypothesis and to provide the most precise value of V_{ud} (the up–down quark-mixing element of the Cabibbo–Kobayashi–Maskawa (CKM) matrix) which is used to test the unitarity of the CKM matrix, the corrected $\mathscr{F}t$ values are extracted from the experimental ft values for the super-allowed Fermi β decays combined with several corrections. One of these indispensable corrections, δ_{C}, depends on the degree of isospin impurity and can only be obtained from theoretical calculations [4, 6]. Rich experimental information on isospin impurity will help to make these calculations more accurate.

Much effort has been made to extract the degree of isospin impurity in a nuclear state by measuring particular reactions, decays, and transitions that should be strictly forbidden by the isospin selection rules if isospin symmetry held perfectly. Observations of violations of these selection rules provide the experimental indications of isospin impurity. There are two popular methods used in this research. One is searching for the electric dipole (E1) transitions between $T = 0$ states, however, it is only applicable for self-conjugate nuclei [7, 8]. The other is the investigation of Fermi β decays between states with different isospin, and it can be applied to states with $T \neq 0$, *i.e.*, $N \neq Z$ nuclei [9].

In a pure Fermi β decay, where only the isospin projection of $T_z = (N-Z)/2$ is changed by the isopin raising or lowering operator, only one single state, called isobaric analog state (IAS), which has the same spin-parity and isospin as the decay precursor, is populated in the final nucleus. Isospin symmetry prevents any fragmentation of the Fermi transition strength, and the sum rule is totally exhausted by the IAS. Furthermore, the proton emission from the IAS to the ground state is, in principle, forbidden by the isospin selection rules, also if the IAS is highly proton unbound [10, 11]. As a result, either the fragmentation of the Fermi transition [12] or the β-delayed isospin-forbidden proton emission [13] can be used to probe the isospin impurity. Direct mass measurements of the involved ground states and isomers are crucial to construct a correct β-decay scheme and thus to determine the isospin impurity.

In this paper, we present a direct mass measurement of the ground state and the low-lying 2^+ isomeric state in ^{52}Co using the Isochronous Mass Spectrometry (IMS) at the Cooler Storage Ring (CSR) accelerator complex [14] of the Heavy Ion Research Facility in Lanzhou (HIRFL). The experimental data has been already published [15]. We will give here a brief description of the experiment and the data analysis, and then discuss the reconstruction of the ^{52}Ni β-decay scheme as well as the isospin impurity in the $T = 2$ IAS in ^{52}Co.

2. Experiment

In the experiment, the isotopes of interest were produced using a ^{58}Ni^{19+} primary beam with the energy of 467.91 MeV$/u$ from the main cooler-storage ring (CSRm), which was operating as a heavy-ion synchrotron. The primary beam impinged on a ~ 15 mm thick beryllium target placed at the entrance of the in-flight fragment separator RIBLL2 [16]. The reaction products from projectile fragmentation of ^{58}Ni emerged from the target and were selected by RIBLL2 and then injected into another cooler-storage ring CSRe working in the isochronous ion-optical mode with the transition energy of $\gamma_{\rm t} = 1.400$. Both RIBLL2 and CSRe were set to a fixed magnetic rigidity of $B\rho = 5.8574$ Tm for optimum transmission of ^{52}Co^{27+} ions.

The revolution times T of ions stored in the CSRe are a function of their mass-to-charge ratios m/q and their velocities v, which can be expressed in the first order approximation as follows [17, 18]:

$$\frac{\Delta T}{T} \approx \frac{1}{\gamma_{\rm t}^2}\frac{\Delta(m/q)}{m/q} - \left(1 - \frac{\gamma^2}{\gamma_{\rm t}^2}\right)\frac{\Delta v}{v}\,, \tag{1}$$

where γ is the the relativistic Lorentz factor. In the isochronous mode [16], for a certain ion species, the faster ions always circulate on longer orbits than the slower ones. The energy of the primary beam was chosen such that the isochronous condition $\gamma \approx \gamma_{\rm t}$ has been fulfilled. Hence, the velocity spread of the injected ions is compensated by their orbit lengths and thus the revolution times directly reflect the m/q ratios of the stored ions. According to Eq. (1), the mass-resolving power for each ion species depends critically on the relative momentum difference $\frac{\Delta v}{v}$. In order to improve the mass-resolving power, we installed a slit at the dispersive plane of straight section of CSRe in order to limit momentum acceptance, but at the cost of lower transmission of the secondary beam. A good compromise has been found for the width of the slit equal to 60 mm.

The revolution times of the stored ions were measured using a dedicated time-of-flight detector [19]. The resolving power of mass spectrometry at CSRe is deteriorated by the instabilities of magnetic fields which cause small shifts of the entire revolution time spectra measured for different injections.

A correction method described in Ref. [20] has been applied in the data analysis to minimize such influence. Figure 1 presents a part of the corrected spectrum zoomed on the time window of 600 ns $\leq T \leq$ 620 ns, and the insert shows the well-resolved peaks of the ground and (2^+) isomeric states of ^{52}Co. The identification of the peaks in the spectrum was done as in Ref. [21]. In order to calibrate the spectrum, a third-order polynomial was fitted to the m/q values as a function of the revolution time T, for all nuclides with accurately known masses [22] (see Fig. 1). The unknown masses were determined by interpolating the fit function to the corresponding times T. The mass excess (ME) values of the ground state and the isomer in ^{52}Co were determined to be $-34361(8)$ keV and $-33974(10)$ keV, respectively. More details of the data analysis can be found in Refs. [15, 20, 21, 23, 24].

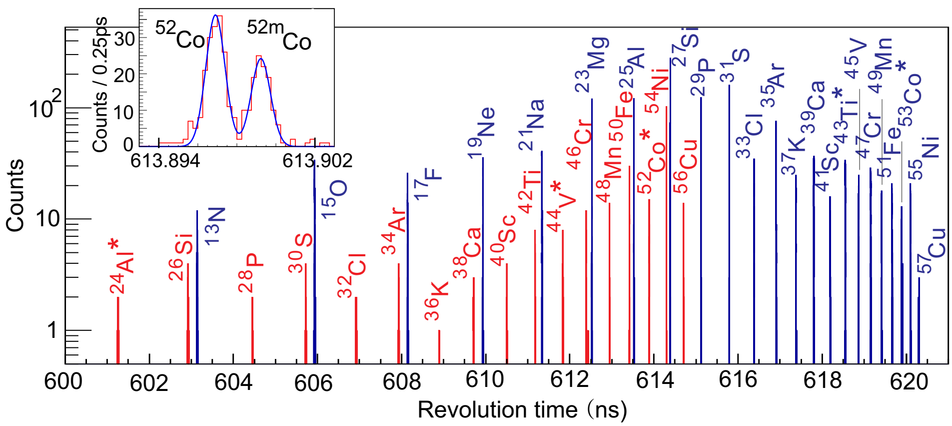

Fig. 1. (Colour on-line) Part of the revolution time spectrum zoomed on the time window of 600 ns $\leq t \leq$ 620 ns. The light grey/red and dark grey/blue peaks represent the $T_z = -1$ and $-1/2$ nuclei, respectively. The asterisks mean that the corresponding peak contains contributions from both ground and isomeric states. The insert shows the well-resolved peaks of the ground and (2^+) isomeric states of ^{52}Co.

3. Discussion and prospects

In the past three decades, three experiments were performed at GANIL to study the ^{52}Ni β decay [25–27], with the detection of β-delayed protons and γ rays. The results of these experiments are consistent. In the construction of a partial scheme of ^{52}Ni β decay, the strongest proton group with a decay energy of 1352 keV was identified as the proton emission from the $T = 2$ IAS in ^{52}Co, as it is conventionally done, and the cascade of 2407 and 141-keV γ rays was also attributed to the IAS. The total branching ratio to populate the IAS in this assignment was very close to the theoretical calculation of the ^{52}Co IAS feeding in the ^{52}Ni β decay. This was interpreted as evidence for this assignment, although it could not be verified if the energies match due to unknown masses of the ground state and of the 2^+ isomer in ^{52}Co.

Taking into account our recently measured mass of the ^{52}Co isomer and the cascading γ rays, a new level has been established corresponding to the highest feeding in β decay, and it has thus been assigned to be the new $T = 2$ IAS in ^{52}Co. This assignment can be verified by applying the Isobaric Multiplet Mass Equation [28]. The main modification of the ^{52}Co level scheme is that we attribute now the strongest proton group to the decay of the lower 1^+ state rather than to the IAS. Furthermore, in the high-statistics proton spectrum in Fig. 16 of Ref. [27], there is no visible sign of the proton decay from IAS besides the strongest proton group. We can thus conclude that the proton decay from IAS is negligibly small. More details concerning the new assignment can be found in Ref. [15]. The comparison of the old and new partial schemes of ^{52}Ni β decay is shown in Fig. 2.

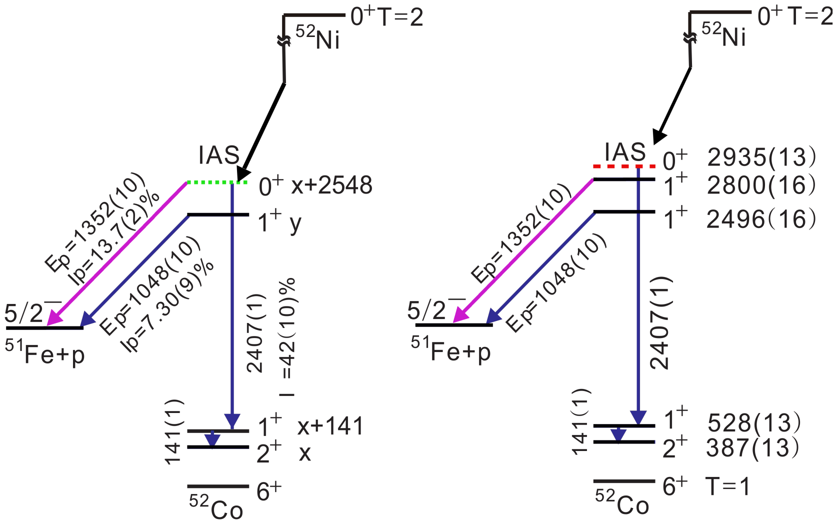

Fig. 2. (Colour on-line) Left: old partial decay scheme of ^{52}Ni β decay based on the conventional rule of β-delayed proton assignment. Right: the new one based on recently measured masses of ground and (2^+) isomeric states in ^{52}Co. The dotted (green) and dashed (red) lines represent the $T = 2$ IAS in the old and new decay scheme, respectively. The information of β-delayed protons and γ rays is taken from the most recent experiment [27].

Another experiment concerning the ground and 2^+ isomeric states of ^{52}Co studied using the JYFLTRAP double-Penning-trap mass spectrometer has been reported recently [29]. The ME values determined in this experiment are −34331.6(66) keV for the ground state and −33974(10) keV for the isomer. The results of the JYFL experiment are in general consistent with those presented here, giving the same conclusion concerning the partial scheme of the ^{52}Ni β decay.

Smirnova *et al.* [30, 31] have proposed a method in which the experimental ratio of β-delayed protons to β-delayed γ rays depopulating an IAS can be used to determine the degree of isospin impurity with the help of shell-model input. In this spirit, the β-delayed proton emission strength compared to the theoretical feeding of IAS also can be regarded as a qualitative indicator of the isospin impurity, since experimental data on β-delayed γ rays are not available for many cases. Table I presents the available β-delayed proton emission strengths of $T_z = -2$ nuclides in the fp shell. The missing two nuclides ^{54}Cu and ^{42}V are known to be proton-unbound [22]. One can notice that the decay strengths from IAS of ^{52}Ni, ^{48}Fe and ^{44}Cr are by one order of magnitude smaller than the others, while the predicted feeding strengths are comparable. We can qualitatively conclude that the isospin impurities in IAS of these three nuclides are much smaller than in other fp nuclei.

TABLE I

Compilation of experimentally determined proton decay strengths and theoretical feeding of IAS as a super-allowed β branch. The γ de-excitation strength of IAS is listed wherever available. All values are in %. Data are taken from Refs. [25–27] except for ^{52}Ni.

Decay precursor	Proton strength	γ strength	Theoretical feeding*
^{56}Zn	18.8(10)	16.3(49)	54
^{52}Ni	$\approx 0^\star$	42(10)	66
^{50}Co	42.0(22)	**	46
^{48}Fe	4.8(3)	30(5)	45
^{46}Mn	17.3(15)	**	35
^{44}Cr	1.7(3)†	**	28
^{40}Ti	25.2(6)	**	30

*The Q_{EC} values used in the prediction are from AME2012 [22].
**No experimental data at present.
*This work.
†2.7(5) in Ref. [32].

In principle, the degree of isospin impurity is small since the isospin symmetry breaking interaction is much weaker than the strong interaction. A possible scenario, where the overlap between the wave functions of the involved states would increase and the isospin impurity would be enhanced, is related to a presence of another state ($|T_2\rangle$) with the same spin-parity but different isospin near the IAS ($|T_1\rangle$). The admixture can be estimated using the perturbation theory

$$\Psi_1 = |T_2\rangle + \frac{\langle T_1|V_{\mathrm{INC}}|T_2\rangle}{E_2 - E_1}|T_1\rangle\,, \tag{2}$$

where $\langle T_1|V_{\mathrm{INC}}|T_2\rangle$ is the matrix element of the INC Hamiltonian. The isospin impurity is determined by both the INC Hamiltonian and the energy difference $E_2 - E_1$ of unperturbed levels. Recently, higher order $T = 1$, $J = 2$ interactions in the *sd* shell have been additionally introduced by Kaneko *et al.* [33], and their important role in elucidating the large isospin impurity observed in the ^{31}Cl β decay and the small isospin impurity observed for ^{23}Al was unambiguously demonstrated. Such investigations in the *fp* shell for the extremely small isospin impurities observed in the ^{52}Ni, ^{48}Fe and ^{44}Cr β decay are highly recommended.

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