Article ID: 1007-4627(2016) 02-0225-05

Comparison of β-decay and Charge-exchange Reactions in Mirror $T=2$ Nuclei and Isospin Mixing

B. Rubio[1], S. E. A. Orrigo[1], A. Algora[1], B. Blank[2], Y. Fujita[3,4], H. Fujita[3], E. Ganioğlu[5], W. Gelletly[6,1], A. Montaner-Piza[1], A. Poves[7]

(*1. Instituto de Física Corpuscular(CSIC-Uni. Valencia), Valencia E-46071, Spain;*
2. Centre d'Etudes Nucléaires de Bordeaux Gradignan, CNRS/IN2P3 - Univ. Bordeaux, Gradignan Cedex, 33175, France;
3. Department of Physics, Osaka University, Toyonaka-Osaka, 560-0043, Japan;
4. Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan;
5. Department of Physics, Istanbul University, Istanbul 34134, Turkey;
6. Department of Physics, University of Surrey, Guildford, Surrey GU2 7XH, UK;
7. Departamento de Física teórica and IFT, UAM-CSIC, Universidad Autónoma de Madrid, Madrid E-28049, Spain)

Abstract: We have carried out β decay studies of proton rich nuclei in the *fp* shell at different laboratories. Here we present our recent results on the β decay of $T_z=-2$ nuclei performed at GANIL and compare them with the Charge Exchange reactions on their stable, mirror-partner targets, performed at RCNP. In one of the cases, the ^{56}Zn - ^{56}Fe pair, a strong isospin mixing has been observed. The results are well reproduced in the framework of Shell Model calculations.

Key words: β-delayed proton; γ decay; isospin mixing; Charge-Exchange reaction; Shell Model

CLC number: O571.42; **Document code:** A **DOI:** 10.11804/NuclPhysRev.33.02.225

1 Introduction and status of the investigation

We have performed a series of experiments focussed on the β-decay of $N\sim Z$ nuclei in the fp shell. Among other interesting points we wanted to study how well iso spin symmetry works in this region by comparing the β decays of proton-rich nuclei with the Charge Exchange reactions on their stable, mirror-partner targets. The Charge-Exchange reactions were performed at the Grand-Raiden spectrometer of the Osaka laboratory RCNP which today provides the best possible energy resolution for studies of this kind of reaction[1]. The β-decay experiments were performed at several different laboratories. Firstly we studied the $T_z=-1$ nuclei ^{54}Ni, ^{50}Fe, ^{46}Cr and ^{42}Ti at GSI with the fragment separator and published the results in Ref. [2]. These were the simplest cases one could choose since the final states were identical for each pair of mirror nuclei and we could directly compare mirror transitions with the only difference being the initial state. In Ref. [2] we discussed how well the mirror symmetry works and the differences between the two probes, one governed by the Weak interaction and the other by the Strong interaction. The results of these studies have been used by Towner and Hardy[3] to calculate radiative and isospin symmetry breaking corrections for the superallowed $0^+\to0^+$ Fermi transitions in these four cases.

Subsequent experiments were performed at the GANIL/LISE fragmentation facility and were focussed on the study of the β decays of the $T_z=-2$ nuclei. Here we studied the β-decay of ^{48}Fe, ^{52}Ni and ^{56}Zn and the results were published in Refs. [4-5], where a thorough explanation was given of the details of the experiment and analysis and their interpretation.. Re-

Received date: 20 Oct. 2015;
Foundation item: Spanish MICINN (FPA2008-06419-C02-01, FPA2011-24553, FPA2014-52823-C2-1-P); Centro de Excelencia Severo Ochoa del IFIC (SEV-2014-0398); Junta para la Ampliación de Estudios Programme (CSIC JAE-Doc contract) co-financed by FSE; ENSAR project (262010); MEXT, Japan (18540270, 22540310); Japan-Spain coll. Program of JSPS and CSIC; UK Science and Technology Facilities Council (STFC) (ST/F012012/1); TUBITAK 2219 International Post Doctoral Research Fellowship Programme
Biography: B. Rubio(1955–), female, Madrid, Spain, Ph.D./Professor, working on experimental nuclear physics; E-mail: berta.rubio@ific.uv.es.

cently, a third series of experiments was carried out at the Nishina Center in RIKEN and three more $T_z = -2$, ^{60}Ge, ^{64}Se and ^{68}Kr and three $T_z = -1$ nuclei ^{62}Ge, ^{66}Se and ^{70}Kr were produced. The analysis of these data is still in progress.

Returning to a brief description of the experiments at GANIL, the fragments, which were identified off-line by energy loss and time-of-flight, were implanted in a thin Double-sided Silion Strip Detectors(DSSSD), of thickness 300 μm, where the subsequently emitted beta and proton radiation was measured. The use of such a thin DSSSD was essential to achieve good resolution for the detection of the delayed protons. We also measured the γ-radiation detected in an array of EXOGAM CLOVER detectors. As usual in this kind of experiment, the correspondence between the fragment and the following radiation was carried out using the correlation in time as well as in space between the implants and the β-particles exploiting the pixellation provided by the DSSSD, while the gammas were measured in prompt coincidence with the β particles.

2 Results and discussion

For the three cases under study, we see in Figs. 1 ∼ 3, the spectrum of charged-particles emitted following the β-decay and the corresponding Charge-Exchange spectrum. If we look at the energies of the levels excited in the daughter nuclei, we find a remarkable correspondence between the ^{56}Cu and ^{56}Co states, see Fig. 3. In contrast in ^{52}Co and ^{52}Mn the correspondence is very clear for the IAS and the state below, but in the region between 3.1 and 3.7 MeV, the results tell us that more 1^+ levels are populated in the β-decay than in the reaction, see Fig. 2. This seems to be the case in ^{48}Fe and ^{48}Mn as well, where the possible state below the IAS is obscured by the signals left in the DSSSD by the β-particles, see Fig. 1. The three level schemes are presented in Fig. 4 where we see an accumulation of 1^+ levels just above the IAS in both the ^{52}Co and ^{48}Mn nuclei.

Let us now have a closer look at the 0^+ IAS in the three cases. All lie at high excitation energy in comparison with the proton separation energy. In a first approach one would expect them to decay via proton emission. However, this is not the case and what happens is that one observes γ de-excitation in competition with proton-emission. The reason is that the IAS has isospin $T_z = 2$ and the final states in the $T_z = -1/2$ nucleus are expected to have $T_z = 1/2$. In consequence the delayed proton emission is forbidden and should not occur unless some isospin mixing is present in one of the two states involved. This has been discussed

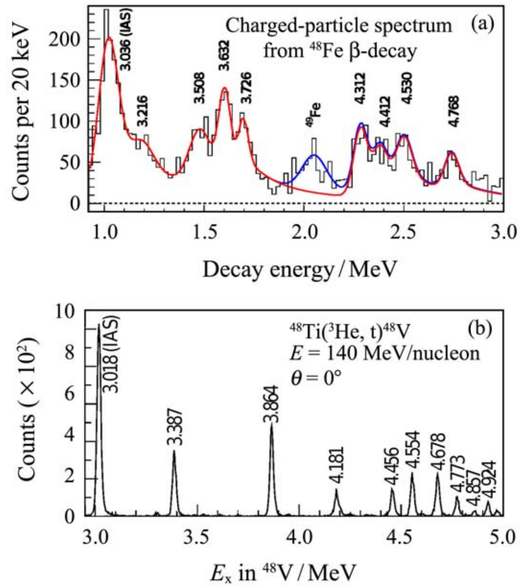

Fig. 1 (color online) (a) DSSSD charged-particle spectrum for the decay events correlated with ^{48}Fe implants[5], where peaks are labelled according to the corresponding excitation energy in the daughter nucleus ^{48}Mn. (b) The spectrum of tritons from the mirror Charge-Exchange reaction, where the peaks are labelled according to the excitation energies of the levels populated in ^{48}Va[9].

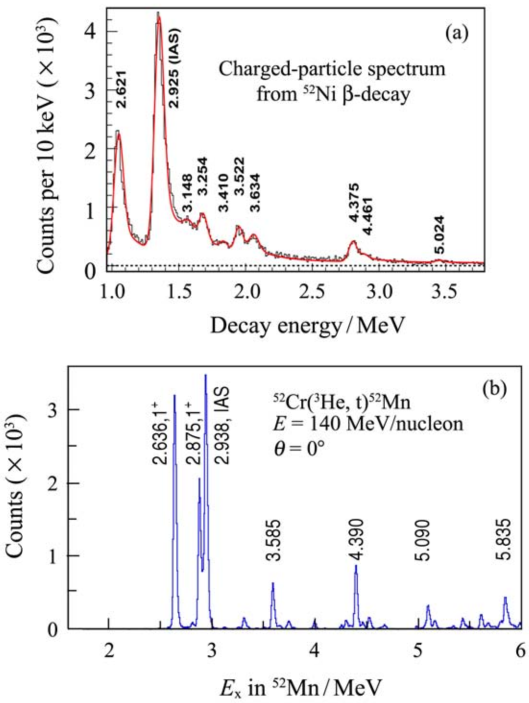

Fig. 2 (color online) (a) DSSSD charged-particle spectrum for the decay events correlated with ^{52}Ni implants[5], the peaks are labelled according to the corresponding excitation energy in the daughter nucleus ^{52}Co. (b) Reaction spectrum for the mirror process, the triton peaks are labelled according to the levels in ^{52}Mn[8].

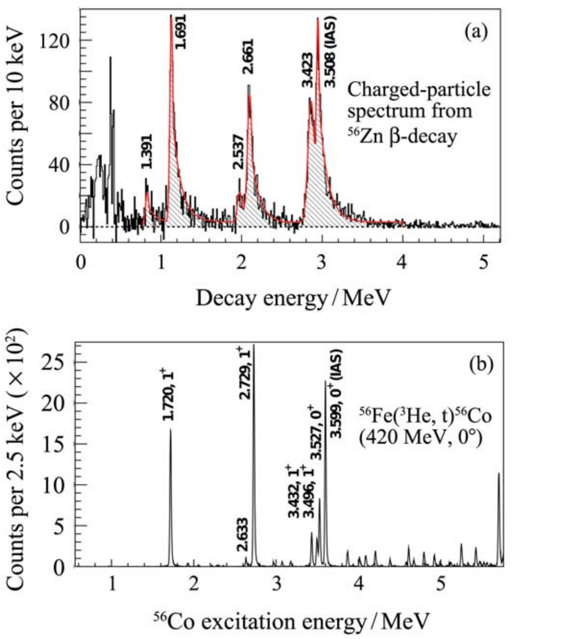

Fig. 3　(color online) (a) DSSSD charged-particle spectrum for the decay events correlated with ^{56}Zn implants[4], the peaks are labelled according to the corresponding excitation energy in the daughter nucleus ^{56}Cu. (b) Reaction spectrum for the mirror process, the triton peaks are labelled according to the levels in ^{56}Co[8].

in several articles, *e.g.* Ref. [6]. Since the IAS is the one which lies at higher excitation energy, it is the one most likely to be mixed. Although it has been known for a long time that isospin mixing occurs, the extent to which it is present in any given state is generally difficult to quantify. The reasons are twofold. Firstly, the mixing matrix element is expected to be small, of the order of dozens of keV, and therefore unless the unperturbed states, susceptible to mixing, lie very close in energy the amount of mixing is small. Secondly there are few probes that are sensitive to the isospin quantum number and therefore capable of indicating the amount of mixing. One of them is the Fermi transition which connects states with identical quantum numbers, including the isospin, with the exception of its third component. The Fermi strength, $B(F)$, tells us the amount of isospin in the daughter state identical to that of the parent state. In general all the $B(F)$ is concentrated in a single state, the IAS, which exhausts the sum rule of $|N-Z|$, but in a few cases, as happens in the decay of ^{56}Zn into ^{56}Cu or in the Charge-Exchange reaction from ^{56}Fe into ^{56}Co two close lying-states which mix, lie very close in energy and mix very strongly.

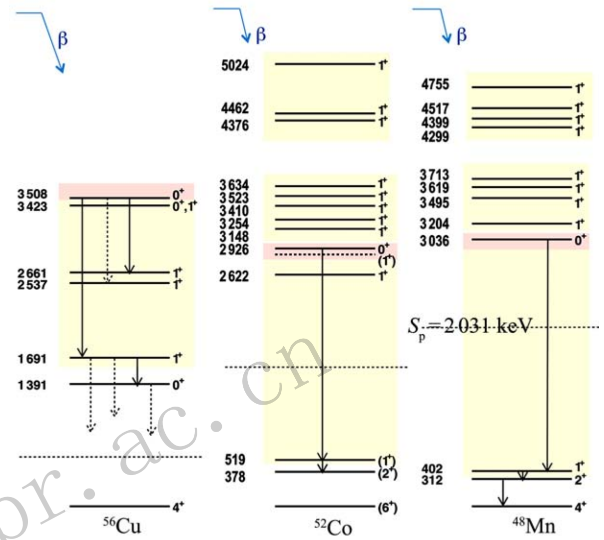

Fig. 4　(color online) Summary of the levels populated in the β-decays of the $T_z=-2$ nuclei ^{56}Zn, ^{52}Ni and ^{48}Fe. The data are taken from Ref. [5] and discussed in the text.

In conclusion, since we observe the proton decay in all three cases, the 0^+ IAS must be a mixed state, but only in one case, in ^{56}Cu, where we observed the population of two states in β-decay and we quantify it.

The amount of mixing can be calculated in a two-level mixing approach, and as has been presented in Ref. [4] for ^{56}Cu and in Ref. [10] for ^{56}Co. The results are summarised in Table 1. As we see, here the amount of mixing is very large. It should be noted that this is not an isolated case in this region. For instance a very similar case was observed in the decay of ^{55}Cu[7], only one proton away from our case.

Table 1　The summary on the calculated results of the amount of isospin mixing for ^{56}Cu and ^{56}Co.

^{56}Cu				^{56}Co			
E_x/keV	$B(F)$	α^2	H_c/keV	E_x/keV	$B(F)$	α^2	H_c/keV
3 508(140)	2.7(5)			3 527(1)	2.89(12)		
		0.33(10)	40(23)			0.28(1)	32.3(5)
3 423(140)	1.3(5)			3 599(1)	1.11(6)		

Let us now take a closer look at the decay of the IAS in ^{56}Cu decay, shown in Fig. 5, where we have explained the reason why we observe the proton decay of the two close lying 0^+ states. What is surprising now is the fact that one of the states (at least), the one lying at 3 508 keV, also decays by electromagnetic transitions, that are inherently much slower than particle emission.

The electromagnetic transition can be inspected in the mirror level in ^{56}Co, at 3 600 keV. It has $t_{1/2} = 2\times10^{-14}$ s, and decays only by γ decay, with the strongest of the three branches having an energy similar to that of the corresponding γ-ray observed in the decay of the ^{56}Cu IAS. This allows us to estimate the 3 508 keV partial γ half-life. The proton half-life of the IAS in ^{56}Cu can be estimated in a simple barrier penetration approach and is of the order of 10^{-18} s, *i.e.* 10^4 times faster. So, it is surprising that the γ-deexcitation competes.

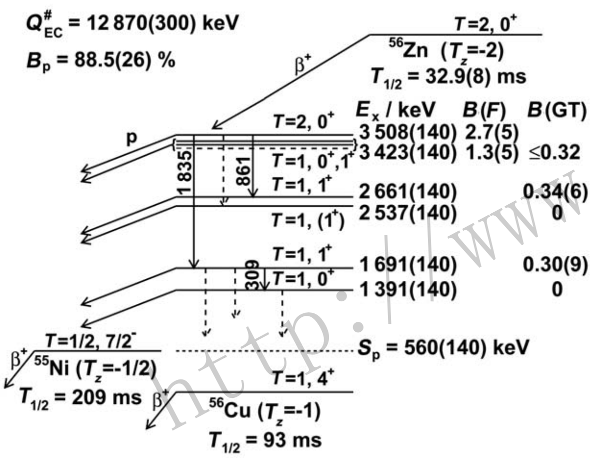

Fig. 5 (color online) ^{56}Zn decay scheme reproduced from Ref. [4]. Observed proton or γ decays are indicated by solid lines. Transitions corresponding to those seen in the mirror ^{56}Co nucleus are shown by dashed lines. The error of 140 keV comes from the uncertainty in S_p.

One possible answer to this dilemma lies in the nuclear structure of the levels involved. In Fig. 6 we sketch the way the decay may proceed. We start with the assumption that the ^{56}Zn ground state (g.s.) has the two extra protons above the $Z = 28$ gap in the $\pi p_{3/2}$ orbital and the two neutron holes in the $\nu f_{7/2}$. From angular momentum conservation arguments, proton decay can only originate from the $f_{7/2}$ orbital leaving a hole there. The final state in ^{55}Ni will involve two particle-hole excitations across the N and $Z = 28$ gaps on top of the $\nu f_{7/2}$ hole (which is the main component of the ^{55}Ni ground state) which should lie high in energy. How much these two wave functions will overlap, expressed in terms of the spectroscopic factor will directly tell us the hindrance of the proton decay.

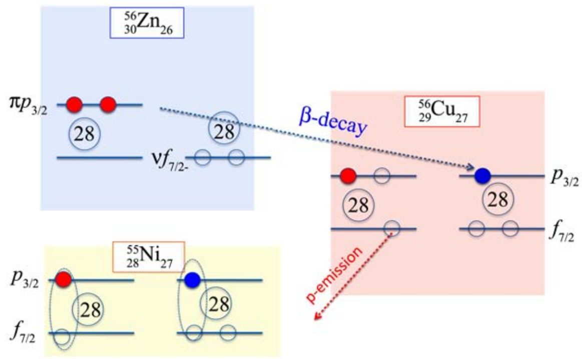

Fig. 6 (color online) A schematic diagram showing a possible explanation for the observed decay of the 0^+ levels populated in ^{56}Cu, see text.

In order to corroborate these ideas we have performed Shell Model calculations using the KB3-GR effective interaction in the *fp*-shell valence space. Preliminary calculations of the low lying 0^+ and 1^+ states are presented in Fig. 7. They reproduce remarkably well the excitation energy of the first 0^+ and 1^+ states as well as the two 0^+ states at 3.5 MeV. Moreover, the calculations predict that these two states, only 17 keV apart, are strongly mixed and have $T = 2$ and $T = 1$ components. The calculated mixing matrix element is 12 keV, close to the experimental value of 40(23) in ^{56}Cu and 32(5) in ^{56}Co. The spectroscopic factor for the proton emission from the $T = 1$ component is 3×10^{-4} very much in accord with the hindrance factor estimated earlier. Moreover the partial half-life of the

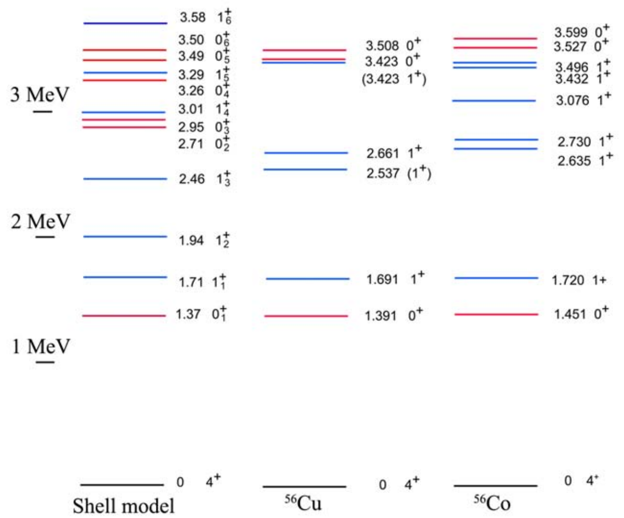

Fig. 7 (color online) Experimental 0^+ and 1^+ known in ^{56}Cu[4] and ^{56}Co[10] and[11] and comparison with the low lying 0^+ and 1^+ calculated in the framework of the Shell Model using the KB3-GR interaction.

electromagnetic transitions, strongly dominated by M1 multipolarity, also reproduce the measured values in ^{56}Co. They will be presented together with an experimental in-beam study of non-yrast states in ^{56}Co[12].

A recent publication by Smirnova *et al.*[13] presented similar calculations to ours. However, their calculations predict the two 0^+ states which mix to be several hundreds of keV apart. The authors have used the experimental results from Ref. [4] to fix the energies of the levels. With this aid, they also reproduce nicely the experimental facts.

Acknowledgements This work was supported by the Spanish MICINN grants FPA2008-06419-C02-01, FPA2011-24553, FPA2014-52823-C2-1-P; Centro de Excelencia Severo Ochoa del IFIC SEV-2014-0398; *Junta para la Ampliación de Estudios* Programme (CSIC JAE-Doc contract) co-financed by FSE; ENSAR project 262010; MEXT, Japan 18540270 and 22540310; Japan-Spain coll. program of JSPS and CSIC; UK Science and Technology Facilities Council (STFC) Grant No. ST/F012012/1; Region of Aquitaine. E.G. acknowledges support by TUBITAK 2219 International Post Doctoral Research Fellowship Programme.

References:

[1] FUJIWARA M, AKIMUNE H, DAITO I, *et al.* Nucl Instr Meth A, 1999, **422**: 484.

[2] MOLINA F, RUBIO B, FUJITA Y, *et al.* Phys Rev C, 2015, **91**: 014301.

[3] TOWNER I S, HARDY J C. Phys Rev C, 2015, **92**: 055505.

[4] ORRIGO S E A, RUBIO B, FUJITA Y, *et al.* Phys Rev Lett, 2014, **112**: 222501.

[5] ORRIGO S E A, RUBIO B, FUJITA Y, *et al.* Phys Rev C, 2016, **93**: 044336.

[6] DOSSAT C, ADIMI N, AKSOUH F, *et al.* Nucl Phys A, 2007, **792**: 18.

[7] TRIPATHI V, TABOR S L,VOLYA A, *et al.* Phys Rev Lett, 2013, **111**: 262501.

[8] FUJITA Y, RUBIO B, Gelletly W. Prog Part Nucl Phys,2011, **66**: 549.

[9] GANIOGLU E, FUJITA H, RUBIO B, *et al.* Phys Rev C, 2016, **93**: 064326.

[10] FUJITA H, FUJITA Y, ADACHI T, *et al.* Phys Rev C, 2013, **88**: 054329.

[11] http://www.nndc.bnl.gov/ensdf/

[12] MONTANER-PIZA A. Ph.D Thesis, University of Valencia, in preparation.

[13] SMIRNOVA N A, BLANK B, BROWN B A, *et al.* Phys Rev C, 2016, **93**: 044305.