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ISOSPIN SYMMETRY OF TRANSITIONS PROBED BY WEAK AND STRONG INTERACTIONS

Y. Fujita[1], J. Äystö[2], M. Oinonen[2] [3], J. Cederkäll[2], L. Fraile[2], S. Franchoo[2], H. Fynbo[2], U. Köster[2], L. Weissman[2], A. Jokinen[3] [4], Z. Janas[5], E. Roeckl[6], V. Fedoseyev[7], V. Mishin[7]

CERN[2]-GSI[6]-HIP[3]-JYFL[4]-Osaka[1]-Troitsk[7]-Warsaw[5] Collaboration

Spokesperson Y. Fujita
Contact person M. Oinonen

Abstract

Under the assumption that isospin is a good quantum number, isospin symmetry is expected for the transitions from the ground states of the pair of $T = 1, T_z = \pm 1$ nuclei to excited states of the $T = 0$ nucleus situated in between the pair. In order to study the isospin symmetry of these transitions, we propose to perform an accurate comparison of Gamow-Teller (GT) transitions for the $A = 58$ system. This system is the heaviest for which such a comparison is possible. The ^{58}Ni($T_z = 1$) → ^{58}Cu($T_z = 0$) GT transitions are presently studied by using high-resolution charge exchange reaction at RNCP Osaka, while those of ^{58}Zn($T_z = -1$) →^{58}Cu will be investigated in the β-decay study at ISOLDE. Due to the large Q_{EC} value of ^{58}Zn, GT transitions can be observed up to high excitation energies in ^{58}Cu. In order to reach this goal, it is proposed to measure β-delayed protons and γ rays by using a dedicated detector array which includes the "Silicon Ball" under development at ISOLDE and the state-of-the-art germanium detectors.

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[1] *Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan*
[2] *ISOLDE, EP Division, CERN, CH-1211 Genève 23, Switzerland*
[3] *Helsinki Institute of Physics, FIN-00014 University of Helsinki, Finland*
[4] *Department of Physics, University of Jyväskylä, FIN-40351 Jyväskylä, Finland*
[5] *Institute of Experimental Physics, University of Warsaw, PL-00681 Warsaw, Poland*
[6] *Gesellschaft für Schwerionenforschung, GE-64291 Darmstadt, Germany*
[7] *Institute of Spectroscopy, Russian Academy of Sciences, RU-142092 Troitsk, Russia*

1 Physics motivation

Under the assumption that the nuclear interaction is charge-symmetric, isospin is a good quantum number. Therefore, a symmetry structure is expected for the isobaric nuclei (isobars) with $\pm T_z$, where T_z is the z component of the isospin defined by $(N - Z)/2$. Although the concept of isospin is widely accepted, the knowledge on isospin symmetry is limited to states in the vicinity of the ground state and mainly to the *sd*-shell nuclei with low A. So far, it is only the isobaric analogue state (IAS) of the ground state that has been extensively studied, yielding Coulomb displacement energies [1] and other interesting physics quantities like isospin mixing [2].

Concerning isospin symmetry at higher excitation energies, we restrict the discussion to analogue transitions. If the analogue nature of states is assumed for isobars, transitions from a given state or its analogue to a daughter state or its analogue should have identical strengths. Therefore, the isospin symmetry can be investigated by comparing the strengths of analogue transitions. This comparison is facilitated by choosing transitions which, due to quantum-mechanical selection rules, select states with specific spin and parity (J^π). Most suitable for this purpose are the $\Delta L = 0$, $\Delta S = 1$ transitions caused by the $\sigma\tau$-type operator, the so-called Gamow-Teller (GT) transitions.

The transition strengths B_{GT} are most directly obtained from β-decay ft values which are derived from the measurements of the Q_{EC} value, the half-life and the branching ratio of the transition of interest. On the other hand, it is known that hadronic charge-exchange (CE) reactions, like (p, n) or (^{3}He,t) reactions, at intermediate incident energies are valuable tools for B_{GT} studies up to high excitation energies of the daughter nucleus [3], since they are not limited by the Q window inherent to β decay. This feature is related to the fact that (i) at 0° the momentum transfer is small and hence the $\sigma\tau$ part of the effective interaction dominates, (ii) the reaction proceeds mainly as a one-step process at intermediate incident energies. The lack of resolution in the pioneering (p, n) work has meanwhile been overcome by the use of (^{3}He,t) reaction. Recently, it has become possible to analyze the triton ejectiles with an energy resolution of well below 100 keV by using a magnetic spectrometer in combination with the dispersion matching technique [4].

The simplest isospin symmetric transitions are found in the odd-mass mirror nuclei with $T = 1/2$. Recently, satisfactory symmetry has been found for the ^{27}Al-^{27}Si pair [5]. In this case, the 0° cross-sections for ^{27}Al(^{3}He,t)^{27}Si reaction were compared to the GT strengths deduced from the $^{27}\mathrm{Si} \rightarrow ^{27}\mathrm{Al}$ β decay for *low* ^{27}Al excitation states. On the other hand, for *higher* ^{27}Al excitation states up to the particle separation energy, the (^{3}He,t) data were compared to the $M1$ γ-strength data from the literature [5]. It is very important to extend such studies to larger T and A nuclei.

The $T_z = 1$ to $T_z = 0$ transitions can been studied in (p, n)-type CE reactions on stable nuclei up to the region of fp-shell nuclei, while the $T_z = -1$ to $T_z = 0$ transitions can be investigated by using β decay. Such studies, however, have been performed so far only for light nuclei, like the $A = 26$ system (^{26}Mg, ^{26}Al and ^{26}Si). A restriction for the symmetry study of light nuclei is that β decays can access only a few low-lying states due to the small Q values.

Among the $T = 1 \rightarrow 0$ candidates, the analogue transitions in the $A = 58$ system, i.e. ^{58}Ni($T_z = 1$) to ^{58}Cu($T_z = 0$) and ^{58}Zn($T_z = -1$) to ^{58}Cu, are well suited for an accurate study of isospin symmetry (see Fig. 1). The former can be studied in the ^{58}Ni(^{3}He,t) reaction, and the latter in the β decay of ^{58}Zn. The $A = 58$ system has the following particularly attractive features both from (^{3}He,t) reaction side as well as from β decay side:

1. Since the ground states of ^{58}Cu and ^{58}Ni have $J^\pi = 1^+$ and 0^+, respectively, the ground-state to ground-state β decay of ^{58}Cu can be used to calibrate the corresponding $B_{\rm GT}$ value obtained from the ^{58}Ni(^{3}He,t)^{58}Cu reaction.

2. Due to its large Q_{EC} value of 9370(50) keV [6], the ^{58}Zn β decay should allow $B_{\rm GT}$ measurements up to high excitation energies of ^{58}Cu.

Concerning point 1, the main part of the GT strength, i.e. the GT Giant Resonance, was observed as a bump-like structure in the pioneering work on the ^{58}Ni(p, n)^{58}Cu [7]. A few years ago, the fine-structure of GT resonance in ^{58}Cu was observed for the first time by using the (^{3}He,t) reaction at 150 MeV/u [8]. In order to study the details of the fine structure, a new beam line was constructed and has recently been commissioned at RCNP, Osaka [4, 9], which enables the accurate realization of dispersion matching [10] for high-resolution measurements. In combination with the spectrometer Grand Raiden [11], an improved resolution of 50 keV has been obtained as shown in Fig. 2. Under these remarkably good experimental conditions, a large number of individual states in ^{58}Cu has been observed.

In the (^{3}He,t) reaction, the $B_{\rm GT}$ values for the transitions to high excitation states are determined by relying on the proportionality between the $B_{\rm GT}$ value and the cross section. In the accurate determination of $B_{\rm GT}$ values, the most important task is to find an accurate and reliable "calibration standard". This task has been performed for the A=58 system in recent precision experiments performed at GSI [12] and Jyväskylä [13], which yielded the ground-state to ground-state branching ratio of the ^{58}Cu decay with an accuracy of 6 parts in 10^3. By combining this result with the new (^{3}He,t) data displayed in Fig. 2, the $B_{\rm GT}$ values for ^{58}Cu excitation energies up to 8 MeV have been determined with good accuracy.

Concerning point 2, i.e. the possibility of reaching high ^{58}Cu excitation-energies in ^{58}Zn β-decay, one has to take into account that the proton-separation energy in ^{58}Cu is rather small ($S_p = 2873(3)$ keV [6]). The detection of β-delayed protons, therefore, is crucial for registering the high-lying GT strengths. Necessary experimental requirements are thus sufficiently high intensity of the mass-separated ^{58}Zn beam, and sufficiently high efficiency and energy resolution of the detectors for β-delayed protons and γ rays. It is clear that the experimental method has to be considerably improved over that used in the pilot experiment on the β decay of ^{58}Zn [14] at ISOLDE, which succeeded in identifying ^{58}Cu levels at 203 and 1051 keV. The technical aspect will be discussed in detail in Section 2.

An interesting side-result of this experiment as well as of the improved ^{58}Zn decay measurement, included in this proposal, is the possibility to confront the experimental B_{GT} data with predictions obtained from large-scale shell model calculations. Experimental data have recently become available or will soon be available from β-decay measurements of fp-shell nuclei such as ^{52m}Fe [15], ^{56}Cu [16, 17] and ^{57}Zn [18]. The extension of these shell-model tests to ^{58}Zn would be of nuclear-physics as well as astrophysics interest.

In summary, we propose to study the isospin symmetry of the analogue transitions $T_z = 1 \rightarrow T_z = 0$ and $T_z = -1 \rightarrow T_z = 0$ for the $A = 58$ case by comparing the high resolution results obtained from the (^{3}He,t) reaction and the β decay up to high excitation energies. Differences in the transition energies and strengths of pairs of analogue transitions will yield information on the breaking of the isospin symmetry. Such effects can be interpreted as being due to effects of the Coulomb interaction and/or the "exotic" structure of nuclei far from the β-stability line.

2 Experimental details

2.1 Target, ion source and mass separation

As the production target, a niobium (Nb) foil was used in the pilot β decay study of ^{58}Zn [14] at ISOLDE, whereas ZrO_2 felt or fiber was used in the previous SC-ISOLDE measurements as discussed in Ref. [19]. In brief, ZrO_2 felt or fiber seems to be the promising target-material for the production of short-lived zinc (Zn) isotopes. Very fast releases for both copper (Cu) and gallium (Ga) isotopes have been observed out of a ZrO_2-fiber target [20]. Similar favourable release behaviour is expected also for Zn isotopes. Thus, part of the proposal is a target test for production of Zn isotopes by using a ZrO_2 target. The actual measurements of the ^{58}Zn decay will then be performed by using either a ZrO_2 or a thin-foil Nb target, depending on the results of the target test. The release of Zn is mainly diffusion- rather than desorption limited and thus the use of thin foils in the target is reasonable.

Although the resonance ionization laser ion source (RILIS) was used during the pilot experiment, the largest contamination of the mass-separated beam consisted of ^{58}Mn ions thermally ionized inside the hot tungsten (W) cavity that forms the ion source. The intensity of the ^{58}Mn beam was at least three orders of magnitude larger than that of ^{58}Zn beam. It is clear that an improvement of the purity of the ^{58}Zn is highly desirable. This can be achieved by selecting a suitable material for the ionizer cavity and by carefully controlling the temperature of the cavity. Since the electron affinity of tantalum (Ta) or Nb is lower than that of W, it is expected that the choice of Ta or Nb would reduce the ionization efficiency for ^{58}Mn by an order of magnitude. A further reduction by an order of magnitude is expected from decreasing the cavity temperature. The effects of the choice of Ta or Nb as cavity material on the release of ^{58}Zn should also be studied during the target test preceding the experiment. It is, however, expected that the effects are small since Zn is an extremely volatile element and is efficiently released from any catcher.

In summary, we are confident that by using the ways discussed above the amount of ^{58}Mn can be reduced to a level being comfortably handled by our detection setup. Further reduction can be obtained with the HRS separator provided that its resolving power exceeds 5000 and the combination of RILIS and HRS can be successfully exploited.

2.2 Detection setup

Mass-separated ^{58}Zn ions will be implanted into a movable tape surrounded by a measurement setup described below. The disturbance from the remaining ^{58}Mn can be minimized by selecting the proper transport frequency of the tape, since the main component of the ^{58}Mn activity is the relatively long-lived ground-state with $T_{1/2} = 65.3$ s. It is expected that by moving the tape after every 5^{th} proton pulse the effect from the Mn activity will be reduced by a factor of 15.

2.2.1 β-delayed proton and γ detection

Two setups will be used, one for β-delayed proton and another for β-delayed γ detection.

Since the measurement of β-delayed proton emission will provide the main part of the β-strength information, a high-efficiency and high-resolution detector for protons is required. The detector has to provide broad energy range from few hundred keV up to several MeV with a simultaneous particle identification capability. Such a high-granularity detector array is under construction at ISOLDE [21] to be used in a variety of different experiments on β-delayed particle and multiparticle decays, as well as in experiments with

REX-ISOLDE. In its first-step version, it provides a 2π solid angle for protons with a 4π trigger detector for β particles. This provides nearly 50% efficiency for proton detection without pile-up with β's, both in singles and in coincidence with β particles. The detector will later be extended to a full 4π version. The full 4π arrangement of detectors will be made of the "football" geometry consisting of 32 hexagons and pentagons, each housing an array of 7 or more detectors. The diameter of the ball will be about 30 cm. The radioactive ion beam is brought into the detector through a small aperture and implanted on thin implantation tape for decay studies or in the case of reaction experiments through a target located in the center of the detector system. Particle identification, which in the case of ^{58}Zn decay concerns resolving protons from β particles, will be based on TOF at low energies and on the pulse shape analysis at higher energies [22]. Low-energy threshold of the detector would be determined by the noise level of the individual detectors and the electronics. This setup is equipped also with a Ge detector to obtain normalization between proton and γ ray intensities. The relative efficiency calibrations between the detectors will be performed using standard sources off-line and with sources produced on-line.

The β-delayed γ measurement will be performed using three VEGA-type [23] or three MINIBALL-type Ge detectors [24] in close geometry around the source position. For instance, with three VEGA-type detectors it is possible to obtain about 6% photopeak efficiency at 1.33 MeV. Thin scintillator detectors will be used in front of the Ge crystals to trigger the acquisition with an emitted β particle. In addition, the Ge detectors can be used to stop the high-energy β-rays due to ^{58}Zn. This will help to identify the γ peaks following the β decay of ^{58}Zn.

2.2.2 Estimations for proton and γ intensities

As mentioned, the S_p in ^{58}Cu is at 2.9 MeV. Assuming the isospin symmetry of the transitions between $^{58}\text{Zn} \rightarrow {}^{58}\text{Cu}$ and $^{58}\text{Ni} \rightarrow {}^{58}\text{Cu}$, the yields of β-delayed protons from the ^{58}Zn decay can be estimated based on the B_{GT} values obtained from the (^{3}He,t) reaction. It is estimated that 3.2% of the total transition intensity lies above the proton threshold of 2873 keV. Two strong transitions would populate the $J^\pi = 1^+$ states at 3.46 and 3.69 MeV observed in the (^{3}He,t) reaction (see Fig. 2 and Ref. [8]). However, the proton emission from these states is hindered by the low Coulomb-barrier penetrability. The strongest proton decay branch is expected to follow the β decay to the 5.14 MeV state. The decay will be identified as a 2.23 MeV proton line, provided it decays to the ground state of ^{57}Ni. Taking into account the penetrability, the total branching for β-delayed proton emission is estimated to be about 1%. The rest will decay via γ emission. This emphasizes the need of a high-efficiency setup of γ detectors in order to observe all the decay strengths including the decays of high-energy γ rays, particularly from the 3.46 and 3.69 MeV states.

2.3 Beamtime request

If one assumes 50% proton detection efficiency, 1% total branching for β-delayed proton emission and a ^{58}Zn beam intensity of 5 atoms/s yield compared to ref. [14], one could detect about 10000 protons in 14 shifts. Requiring 100 events to be counted in the weakest peak observed, this measuring time would allow us to see all the GT strength observed in (^{3}He,t) work (see Fig. 2) up to a ^{58}Cu excitation energy of 6 MeV. During this beamtime we would detect about 100000 events in the 203 keV γ peak (assuming 10% efficiency) which will be used for normalizing the proton and γ intensities. With a separate setup for γ detection, for example three VEGA detectors around the source position, about 250 events in 7 shifts will be detected following the decays of the 3.46 or 3.69 MeV states if assuming reasonable branching ratios of 1% for the β-delayed γ transitions.

Based on the discussion above we ask for

a) 3 shifts for a test with ZrO_2 felt target with Ta ionizer cavity and RILIS tuned for Zn at either GPS or HRS separator

b) 23 shifts with ZrO_2 felt or Nb thin-foil target equipped with Ta ionizer cavity and RILIS tuned for Zn at either GPS or HRS separator (HRS is preferable) divided as follows

- 1 shift for tuning the target and ion source parameters before the run

- 1 shift for on-line calibrations

- 14 shifts for β-delayed proton measurement

- 7 shifts for β-delayed γ measurement

In total we ask for 26 shifts from which 25 shifts with radioactive beam.

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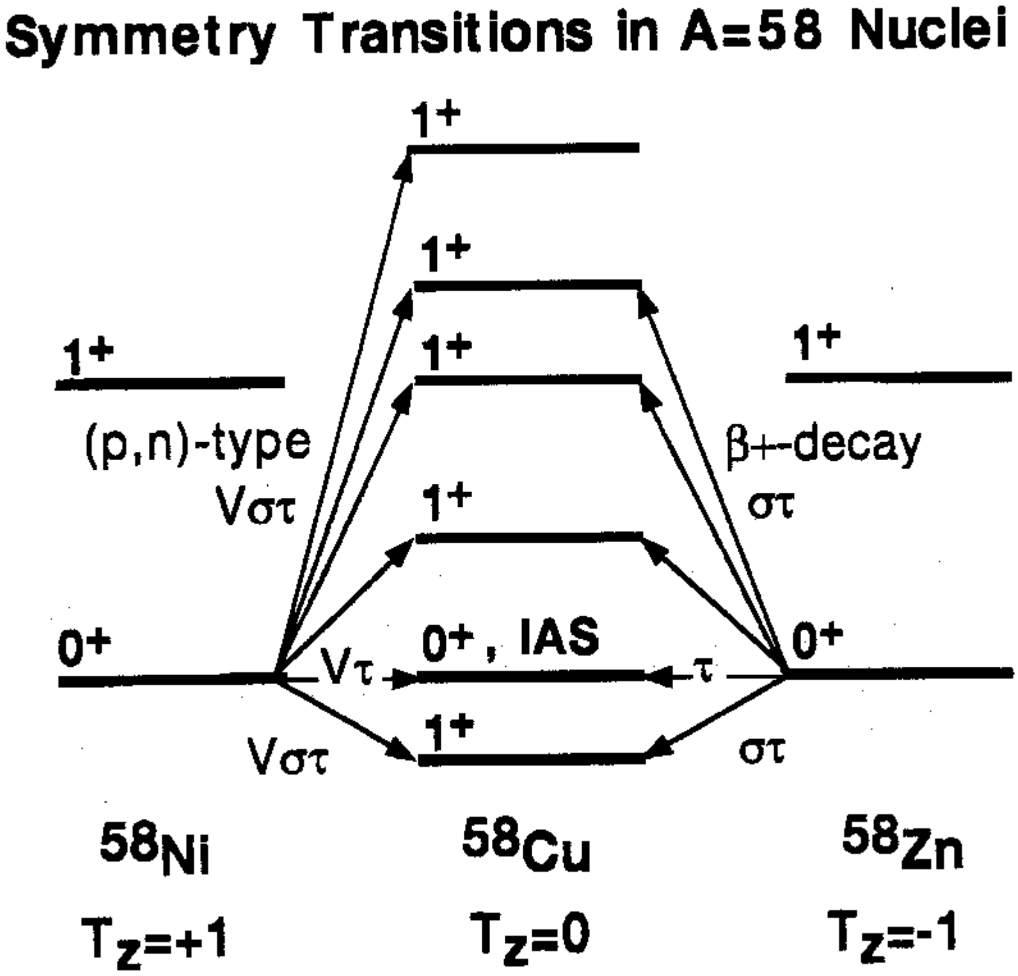
Figure 1: Schematic illustration of the isospin symmetry transitions in $A = 58$ system. The level schemes neglecting Coulomb displacement energies are shown for the better understanding of the isospin symmetry structure of states in different T_z nuclei.

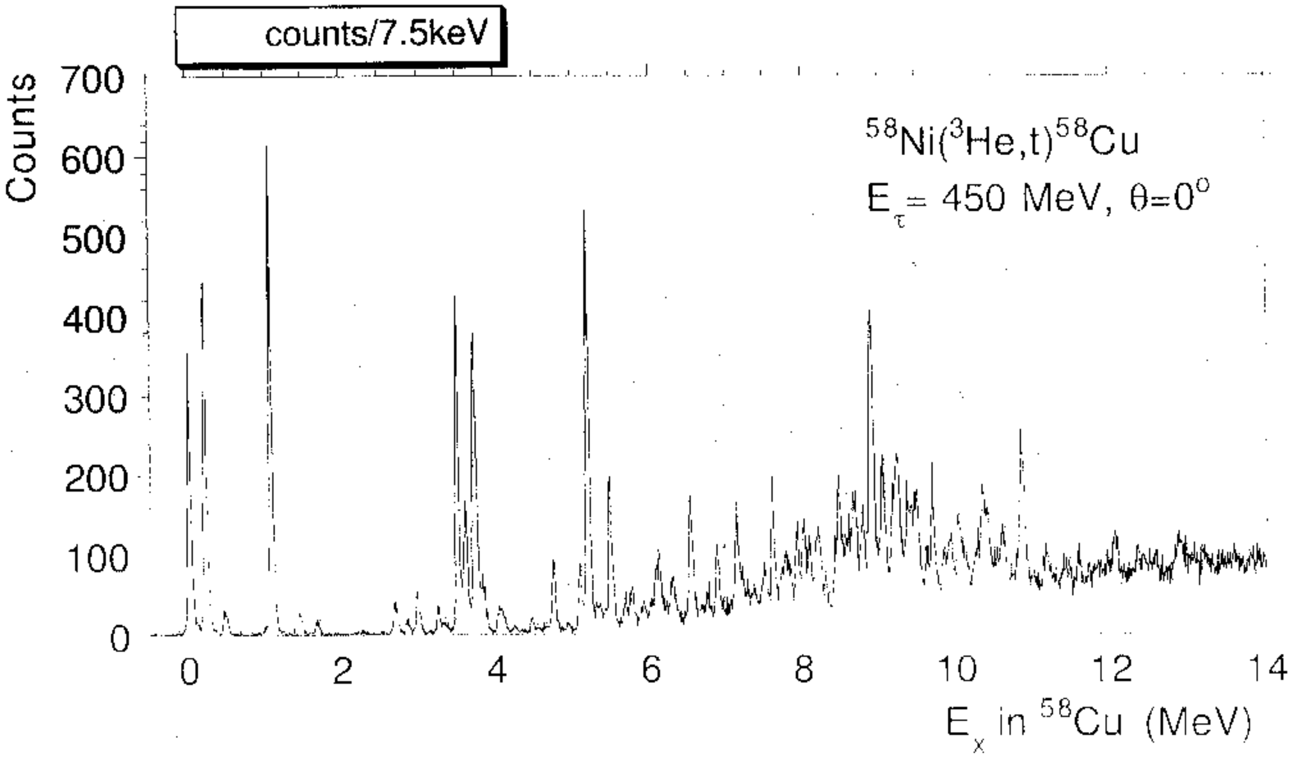
Figure 2: The 0°, ^{58}Ni(^{3}He,t)^{58}Cu spectrum at the incident energy of 150 MeV/nucleon. A resolution of 50 keV was achieved by using the dispersion matching technique. All the prominent peaks are identified to have $L = 0$ character, suggesting that they are GT states, except the 0.203 MeV IAS.

Fig 1.



Symmetry Transitions in A=58 Nuclei

Fig 2.


counts/7.5keV
Counts
700
600
500
400
300
200
100
0
^{58}Ni(^{3}He,t)^{58}Cu
E_τ= 450 MeV, θ=0°
0
2
4
6
8
10
12
14
E_x in ^{58}Cu (MeV)