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Structure of proton-rich nuclei via mirror β decay and charge exchange reactions

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Abstract. The β decays of the proton-rich, $T_z = -2$ nuclei ^{48}Fe, ^{52}Ni and ^{56}Zn were investigated by decay spectroscopy at GANIL. The decay schemes were determined, together with absolute Fermi and Gamow-Teller transition strengths. New interesting results were obtained, including the first observation of a new decay mode in the fp-shell, the exotic β-delayed γ-proton decay seen in ^{56}Zn, and the first observation of the 2^+ isomer in ^{52}Co. These studies were complemented by Charge Exchange reactions on the stable mirror targets.

1. Introduction

One of the main topics in contemporary nuclear physics concerns the study of nuclear structure far from the valley of nuclear stability. Our knowledge of Gamow-Teller (GT) transitions when approaching the proton drip-line is still rather incomplete [1] because the production of such exotic nuclei becomes steadily more challenging. In addition to the great interest from the point of view of nuclear structure, the study of GT transitions starting from unstable proton-rich nuclei is also of crucial importance for nuclear astrophysics since many heavy proton-rich elements are produced in the rp-process passing through proton-rich fp-shell nuclei.

Decay spectroscopy with implanted Radioactive Ion Beams (RIBs) is a powerful tool to explore nuclei at the proton drip-line since the β decay has direct access to the absolute values of the Fermi B(F) and Gamow-Teller B(GT) transition strengths. Charge Exchange (CE) reactions such as (p,n) or $(^3$He,$t)$ are the mirror strong interaction process and provide information on the relative B(GT) values [2] without energy restrictions. Hence β decay and CE studies are complementary tools. Their combined analysis allows us to investigate fundamental questions related to the role of isospin in atomic nuclei, such as isospin symmetry in mirror nuclei [3, 4]. Aiming at these goals, we have performed a series of experiments pointing to compare β decay in proton-rich nuclei and CE reactions on stable mirror targets.

The β decay of the proton-rich, $T_z = -2$ nuclei ^{56}Zn [5], ^{48}Fe and ^{52}Ni [6], and of the odd-odd, $T_z = -1$ nucleus ^{52}Co [7] was studied in an experiment performed at GANIL. New interesting results were obtained, going from the first observation of a new decay mode, the exotic β-delayed γ-proton decay seen in ^{56}Zn [5], to the first observation of the 2^+ isomer in ^{52}Co [7]. In all cases the decay schemes were established, with absolute B(F) and B(GT) strengths.

The results for the $T_z = -2$ nuclei [6] were compared with those obtained by complementary (^{3}He,t) CE reactions carried out on the stable mirror targets at RCNP Osaka [4, 8, 9]. In general, under the assumption of isospin symmetry, one expects that mirror Fermi and GT transitions should populate the same states in the daughter nucleus with the same probability. However, one should note that in the $T = 2$ isospin multiplet we compare transitions involving different initial and final states. For example, the mirror case of the β^+ decay of ^{56}Zn to ^{56}Cu is the ^{56}Fe(^{3}He,t)^{56}Co reaction. Thus the final nuclei (^{56}Cu and ^{56}Co) are not identical and therefore the level scheme and the strengths might be slightly different. Nevertheless, the comparison is very effective in helping shed light on the structure of such exotic nuclei and improving our understanding of their decay schemes, especially for the most exotic cases.

2. The experimental setup

The experiment was performed at GANIL. The production of several exotic nuclei was achieved by fragmenting a primary beam of ^{58}Ni^{26+} at 74.5 MeV/nucleon on a natural Ni target of 200 μm thickness. The fragments were selected by the LISE3 separator [10] and then implanted into a Double-Sided Silicon Strip Detector (DSSSD), 300 μm thick. Both the implanted heavy ions and subsequent charged-particle (β particles and protons) decays were detected by the DSSSD. Four EXOGAM Germanium clovers [11] surrounded the DSSSD in order to detect the β-delayed γ-rays. Particle identification was achieved by using the energy loss signal (ΔE) from a silicon detector placed 28 cm upstream from the DSSSD together with the Time-of-Flight (ToF) signal obtained as the time difference between the cyclotron radio-frequency and the ΔE signal. In addition, an implantation event was defined by simultaneous signals from both the ΔE and DSSSD detectors, while a decay event was defined by a signal above threshold in the DSSSD with no coincident signal in the ΔE detector. More details on the experimental setup and the procedures employed in the data analysis are available in Ref. [6].

3. The β decay of ^{56}Zn

^{56}Zn, lying at the proton drip-line, has been one of the most intriguing cases under study in our experimental campaign. In this nucleus we observed many interesting and unusual features [5], reflecting the peculiarities that one might expect when investigating the most exotic systems.

The ^{56}Zn decay scheme is shown in figure 1. One can see that there is competition between β-delayed proton and β-delayed γ emission in the decay. Moreover, the β-delayed γ rays populate levels in the daughter nucleus, ^{56}Cu, which lie above the proton separation energy and hence are unbound. Thus these levels then decay by proton emission to the ground state of ^{55}Ni. Therefore the sequence observed is β-delayed γ-proton decay, a new and exotic decay mode seen here for the first time in the fp-shell. In ^{56}Zn we observed three such sequences, involving the γ rays at 1835, 861 and 309 keV and the ^{56}Cu levels at 1691, 2661 and 1391 keV, respectively.

The comparison between the β decay of ^{56}Zn to ^{56}Cu [5] and the mirror CE process, the ^{56}Fe(^{3}He,t)^{56}Co reaction [8], shows a remarkable isospin symmetry where all the dominant transitions are observed in both cases and with very similar strengths. Hence we exploited the higher energy resolution ($\sim$ 30 keV) of the CE reaction to clarify other aspects of the level structure in ^{56}Cu which, without this comparison, would have remained unclear. The Fermi transition feeds the Isobaric Analogue State (IAS), which has $T = 2$ in this isobaric multiplet. It was observed in ^{56}Co [8] that the IAS is fragmented in two 0^+ levels which mix (with 28% in the $T = 1$ state) and both contribute to the Fermi strength. Based on this evidence we assumed that there is a similar situation in ^{56}Cu. In other words the Fermi strength is again divided between two states and we found that isospin mixing of 33% is required to obtain the expected value of $B(\text{F})$, given by the sum rule $|N - Z| = 4$. Later on these findings were also confirmed by two independent shell model calculations [12, 13].

Another intriguing feature emerged when looking in more detail at the decay of the IAS in ^{56}Cu. The proton decay from the $T = 2$ IAS would be isospin-forbidden, however it may proceed thanks to the 33% mixed $T = 1$ component. At this point the much faster proton decay ($t_{1/2} \sim 10^{-18}$ s) should dominate over the γ de-excitation ($t_{1/2} \sim 10^{-14}$ s in the mirror). This is not the case since the competing γ decay from the IAS is still observed. The reason for such behaviour lies in the nuclear structure. Both shell model calculations [12, 13] found the proton decay of the $T = 1$ IAS component hindered by a factor of 10^3.
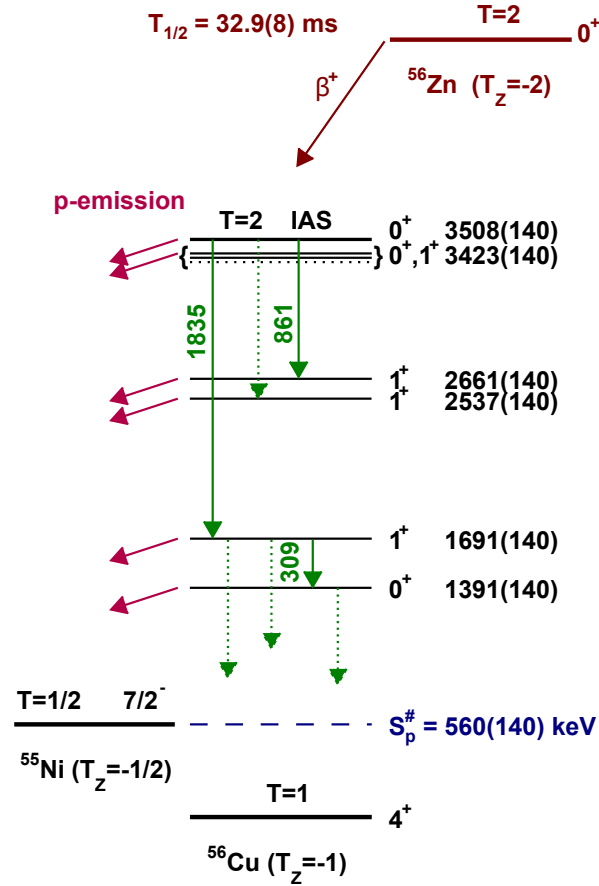

Figure 1. The decay scheme of ^{56}Zn. Transitions corresponding to those observed in the mirror ^{56}Co nucleus are represented by dotted lines.

4. The β decay of ^{48}Fe and ^{52}Ni

In the same experiment we studied the β decay of the $T_z = -2$ nuclei ^{48}Fe and ^{52}Ni [6]. Individual β-delayed protons and γ rays were measured also for these decays. The higher energy resolution achieved for protons, in comparison to a previous study [14], allowed us to identify many new states populated in the decays of ^{48}Fe and ^{52}Ni and to determine the related branching ratios for the first time. The DSSSD spectra were compared with the results from the mirror CE data from the (^{3}He,t) reaction on ^{52}Cr [4] and ^{48}Ti [9], respectively. We observed a good isospin symmetry in the mass 52 case, while the comparison does not work as well in the mass 48 case. The decay schemes obtained for ^{48}Fe and ^{52}Ni are shown in figure 2 and 3, respectively.
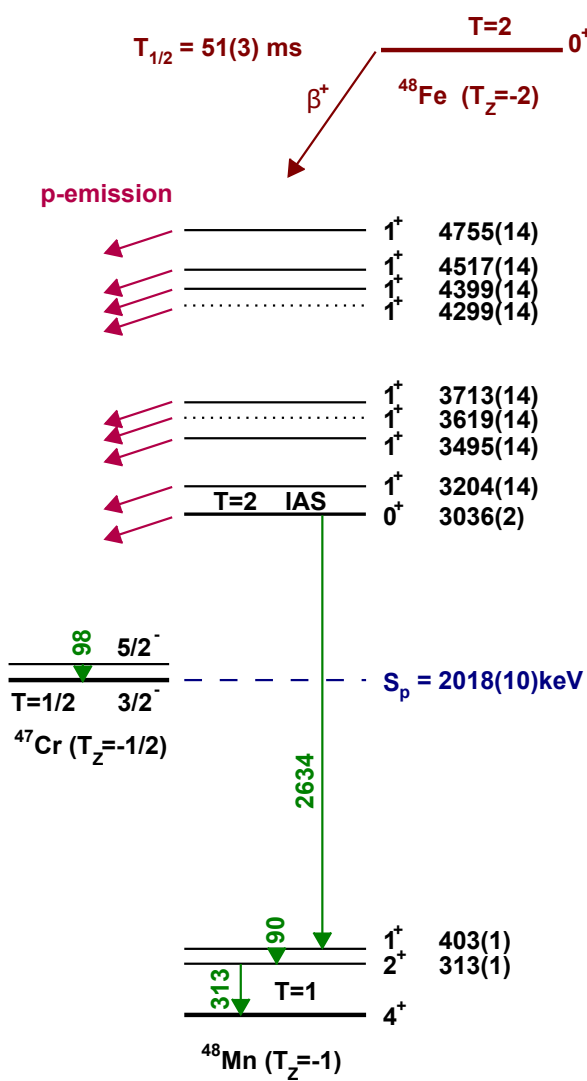
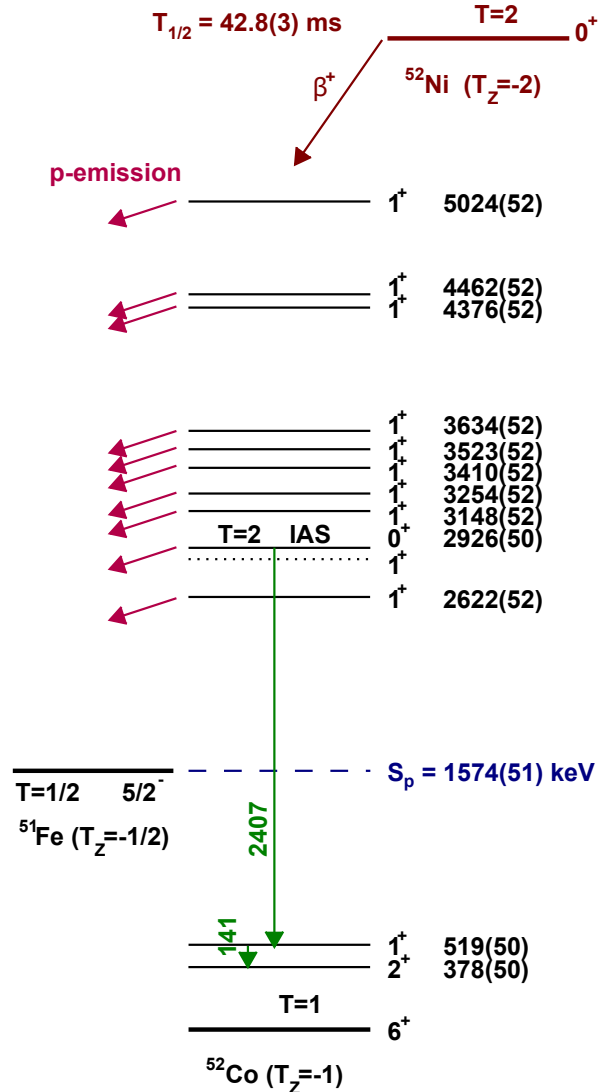**Figure 2.** The decay scheme of ^{48}Fe. For details on the dotted levels see Ref. [6].

Figure 3. The decay scheme of ^{52}Ni. The dotted 1^+ state was seen in the mirror ^{52}Mn.

In the decay of ^{48}Fe and ^{52}Ni we also observed competition between β-delayed protons and β-delayed γ rays in the de-excitation of the $T = 2$ IAS. The β-delayed proton emission would again be isospin-forbidden. It was observed, however, even although it is weaker than in ^{56}Zn and is attributed to a $T = 1$ isospin impurity mixed with the IAS. For ^{48}Fe and ^{52}Ni the β-delayed proton emission constitutes only 14% and 25% of the respective totals compared with 44% in ^{56}Zn. There are two reasons for this difference. Firstly, for the ^{56}Zn daughter there is another 0^+ state less than 100 keV from the IAS and the mixing depends on how close the two states are [15], thus the strong mixing favours proton decay. Secondly it is partly due to the relatively low proton energies involved for the ^{48}Fe and ^{52}Ni daughters. As a result the calculated proton half-lives are of the same order-of-magnitude as the γ-decay Weisskopf transition probabilities.

At the time of our study the masses of the ^{52}Co ground state and its 2^+ isomer were unknown. Hence we estimated the energy of the 2^+ level in figure 3 starting from the mirror ^{52}Mn, as

explained in Ref. [6]. Now that these masses have been measured [16] we find an energy of 387(13) keV for the 2^+ state which agrees well with our estimated value of 378(50) keV. In Ref. [16], based on the new mass measurement, it is proposed that the energy of the IAS in ^{52}Co is 2935(13) keV. It is further suggested that the γ and proton emission do not both arise from the IAS. Instead the proton emission is from a 1^+ state lying below the IAS at 2800(16) keV. However without the proton emission from the IAS 25% of the Fermi strength would be missing. Further experiments are required to address this issue.
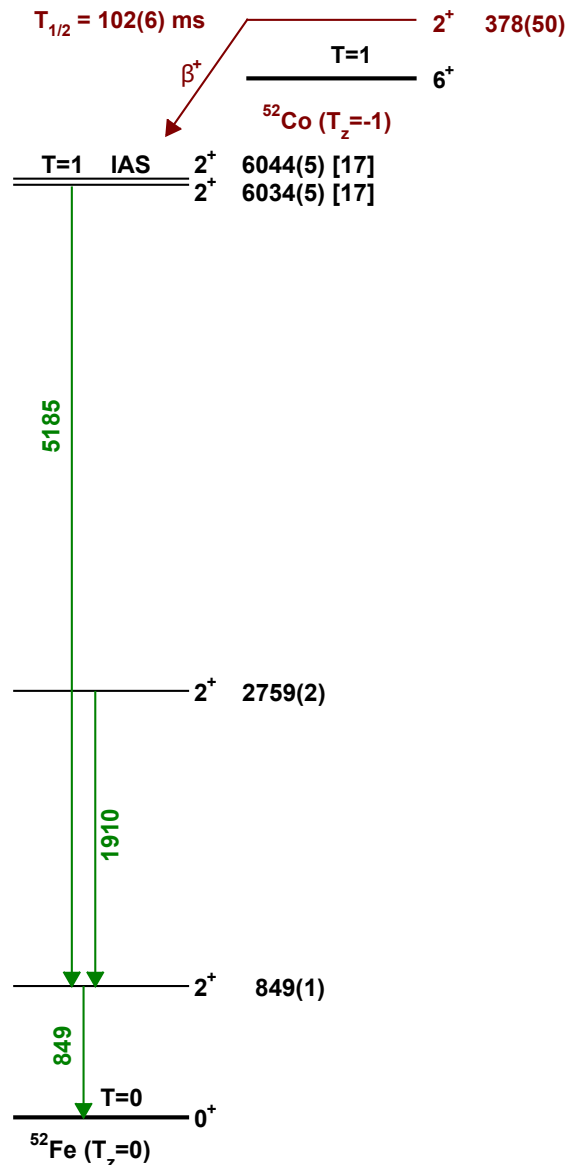

Figure 4. The decay scheme of the 2^+ isomer in ^{52}Co. Two 2^+ levels 10 keV apart are reported as IAS candidates in ^{52}Fe [17].

5. First observation of the 2^+ isomer in ^{52}Co

Odd-odd nuclei are particularly difficult to study because there are often two long-lived states, one of which is the ground state, with similar half-lives. One such case is the $T_z = -1$, ^{52}Co nucleus where it was speculated that an isomeric 2^+ state exists that had not been observed prior

to the present work [7]. The difficulty was that when one attempted to populate ^{52}Co directly both the ground state and the isomer are produced and implanted together. We succeeded in observing the isomer for the first time by creating it as a product of the decay of ^{52}Ni (see figure 3). This decay process directly populates the $0^+(T=2)$ IAS in ^{52}Co, which then de-excites by emitting two γ rays of 2407 and 141 keV, populating in a clean way the 2^+ isomeric state. In this way we were able to disentangle the β decays of the 2^+ isomer and the 6^+ ground state in ^{52}Co. We then observed the β de-excitation of the isomer, shown in figure 4, which is followed by the emission of three γ rays of energy 849, 1910 and 5185 keV. We measured for the first time the half-life of the isomeric state, 102(6) ms, and improved the half-life measurement for the ground state, 112(3) ms [7].

6. Conclusions

We studied the β decay of a variety of proton rich-nuclei, namely ^{48}Fe, ^{52}Ni, ^{52}Co and ^{56}Zn, establishing the decay schemes and absolute values for the transitions strengths. For the $T_z = -2$ cases we have seen that the comparison with the CE data was very useful to better understand some aspects of the decays. Mirror symmetry works well in general, but some differences remain. The decay of ^{56}Zn showed many exotic features, such as the IAS fragmentation due to strong isospin mixing, the unexpected competition between β-delayed protons and β-delayed γ rays from the IAS, later explained as due to the nuclear structure of the states involved, and the first observation of the β-delayed γ-proton decay in the fp-shell. Another remarkable result is the discovery of the 2^+ isomer in ^{52}Co, with the first measurement of its half-life and de-exciting γ rays.

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