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## Beta decay of the $T_z=-2$ nucleus $^{64}\text{Se}$ and its descendants

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**Abstract.** The beta decay of the  $T_z=-2$  nucleus  $^{64}\text{Se}$  has been studied in a fragmentation reaction at RIKEN-Nishina Center.  $^{64}\text{Se}$  is the heaviest  $T_z=-2$  nucleus that decays to bound states in the daughter nucleus and the heaviest case where the mirror reaction  $^{64}\text{Zn}(3\text{He},t)^{64}\text{Ga}$  on the  $T_z=+2$   $^{64}\text{Zn}$  stable target exists and can be compared. Beta-delayed gamma and proton radiation is reported for the  $^{64}\text{Se}$  and  $^{64}\text{As}$  cases. New levels have been observed in  $^{64}\text{As}$ ,  $^{64}\text{Ge}$  ( $N=Z$ ),  $^{63}\text{Ge}$  and  $^{63}\text{Ga}$ . The associated  $T_{1/2}$  values have been obtained.

### 1. Introduction

This paper concerns the study of proton rich nuclei which together with their mirror partners can provide information on isospin symmetry far from the stability. If isospin symmetry works mirror nuclei should have identical structure, just exchanging the number of protons by the number of neutrons, and mirror processes such as charge exchange reactions and beta decay should produce similar results. Based on these ideas we have launched a programme of beta decay experiments at GSI [1], GANIL [2,3] and RIKEN where we have studied the decay of  $T_z=-1$  and  $-2$  nuclei in the  $fp$  shell produced in fragmentation and compared our results with those obtained in  $(3\text{He},t)$  charge exchange reaction experiments on the mirror stable nuclei carried out at RCNP Osaka (see for instance [4]). The first experiments were carried out at GSI and GANIL using either  $^{58}\text{Ni}$  or  $^{64}\text{Zn}$  beams. In these



studies, the heaviest nuclei which could be reached were  $^{56}\text{Zn}$  [2] and  $^{58}\text{Zn}$  [5]. In order to reach  $^{60,62}\text{Ge}$  and  $^{64,66}\text{Se}$ , an intense beam of  $^{78}\text{Kr}$ , only available at the RIKEN Nishina center, was necessary. Here we present preliminary results from the RIKEN campaign on the decay of  $^{64}\text{Se}$  and its descendants.

## 2. The experiment

The nuclei of interest were produced at the RIKEN Nishina Center using the fragmentation of a 345 MeV  $^{78}\text{Kr}$  beam with unprecedented intensity (up to 300 particle nA) on a Be target. The fragments were separated in flight using the BigRIPS separator [6] and implanted in three 1mm thick WAS3ABi double-sided Si strip detectors (DSSSD) [7] each of them having an active area of  $60 \times 40 \text{ mm}^2$  segmented into 60 vertical by 40 horizontal strips. The implantation setup was surrounded by the EUROBALL-RIKEN Cluster Array (EURICA) [8], 12 CLUSTER-detectors of Euroball type, each one consisting of seven tapered hexagonal HPGe crystals at a nominal distance of 22 cm from the center of WAS3ABi. Three different settings of BigRIPS were used in this experiment, the first two were optimised for the production of  $^{60}\text{Ge}$ ,  $^{62}\text{Ge}$  and  $^{64}\text{Se}$  nuclei and the third one for  $^{66}\text{Se}$ . Putting conditions on the ToF and DeltaE signals of the ions we have produced the identification plots corresponding to these three settings and they are shown in Figure 1 and table 1.

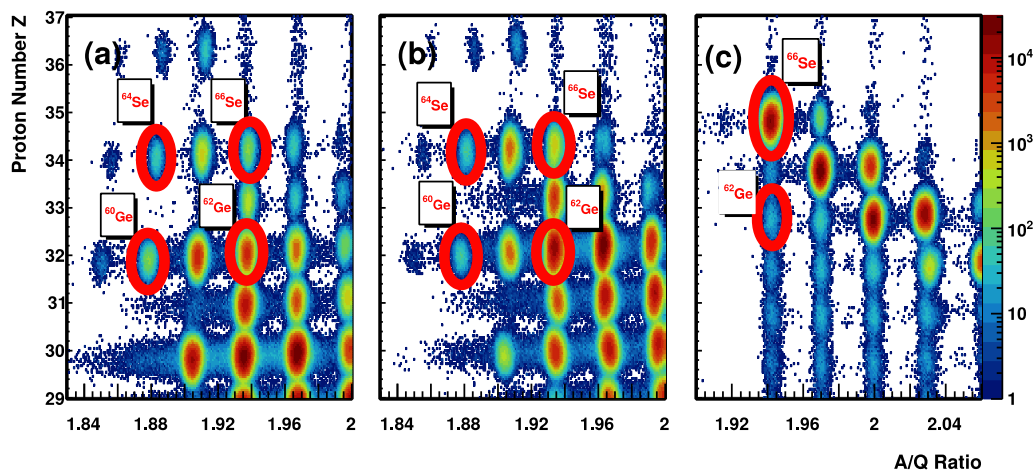


Figure 1. Particle identification plot for the three Big-RIPS settings used at Nishina Center–RIKEN. The first two, (a) and (b) were optimised for the production of  $^{64}\text{Se}$ ,  $^{62}\text{Ge}$  and  $^{60}\text{Ge}$ , and (c) was set for  $^{66}\text{Se}$ .

Nucl.	Number of Implanted Ions per setting			Total Implanted
$^{64}\text{Se}$	3829	6479	-	10308
$^{64}\text{As}$	23446	457474	976	481896
$^{63}\text{Ge}$	117059	3741115	2798	3860972
$^{66}\text{Se}$	11538	78634	952026	1042198

Table 1: Number of implanted ions for the nuclei of interest in the three settings used in the experiments.

## 3. Results for the decay of $^{64}\text{Se}$ and its descendants

The  $^{64}\text{Se}$  nucleus is an interesting case to study. First of all, it is the heaviest  $T_z=-2$  case where the beta decay can be compared with the charge exchange mirror reaction ( $^3\text{He},t$ ) on the  $^{64}\text{Zn}$  stable nucleus [9], secondly it is the heaviest  $T_z=-2$  nucleus where the decay still proceeds through beta-delayed protons and beta-delayed gamma radiation, thirdly, it is only one neutron away from the last bound selenium isotope,  $^{63}\text{Se}$ , a two-proton emitter [10]. Moreover, the beta-delayed proton decay can populate excited states in the  $T_z=-1/2$  nucleus  $^{63}\text{Ge}$ , a nucleus that cannot be accessed directly by beta decay because  $^{63}\text{As}$  is unbound.

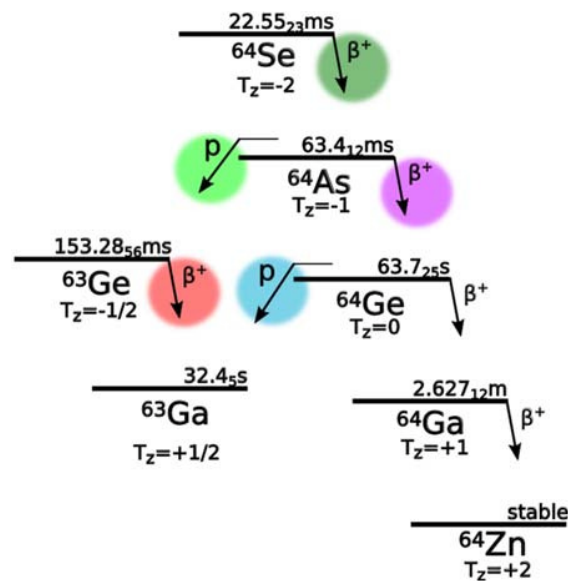


Figure 2. The decay chain associated with  $^{64}\text{Se}$  decay.

No experimental information on the decay properties of  $^{64}\text{Se}$  existed prior to this work. In consequence, a full understanding of all the decays correlated with the implantation of  $^{64}\text{Se}$  ions was mandatory in order to deduce the primary radiation due to  $^{64}\text{Se}$  decay. The decay chain associated with  $^{64}\text{Se}$  is shown in figure 2 where decays shorter than 200 ms are marked in color. A strong beta-delayed proton branching is expected in  $^{64}\text{Se}$  since the proton separation energy in the daughter nucleus  $^{64}\text{As}$  is expected to be of the order of 100 keV according to the last Mass Evaluation tables [11]. In consequence, three beta decays are important here, the nucleus of interest,  $^{64}\text{Se}$ , and the descendants,  $^{64}\text{As}$  and  $^{63}\text{Ge}$ . The gamma spectra associated with the three corresponding implants are presented in figure 3. The gamma radiation is detected in EURICA, the spectra are constructed in add-back mode in prompt coincidence with the beta-particles which happen in time correlation with the implantation conditions. In green, we show the gamma lines that are observed in time correlation with  $^{64}\text{Se}$  implants but not with  $^{64}\text{As}$  or  $^{63}\text{Ge}$ , they are associated with the beta decay of  $^{64}\text{Se}$ . Similarly, the lines marked in pink appear with the condition on  $^{64}\text{Se}$  (as daughter activity) and  $^{64}\text{As}$ , but disappear when the condition is set on  $^{63}\text{Ge}$ , and are thus associated with the beta decay of  $^{64}\text{As}$ . Finally, the gamma lines associated with the decay of  $^{63}\text{Ge}$  are marked in red. No beta-delayed gamma radiation was known in any of these three decays prior to this work.

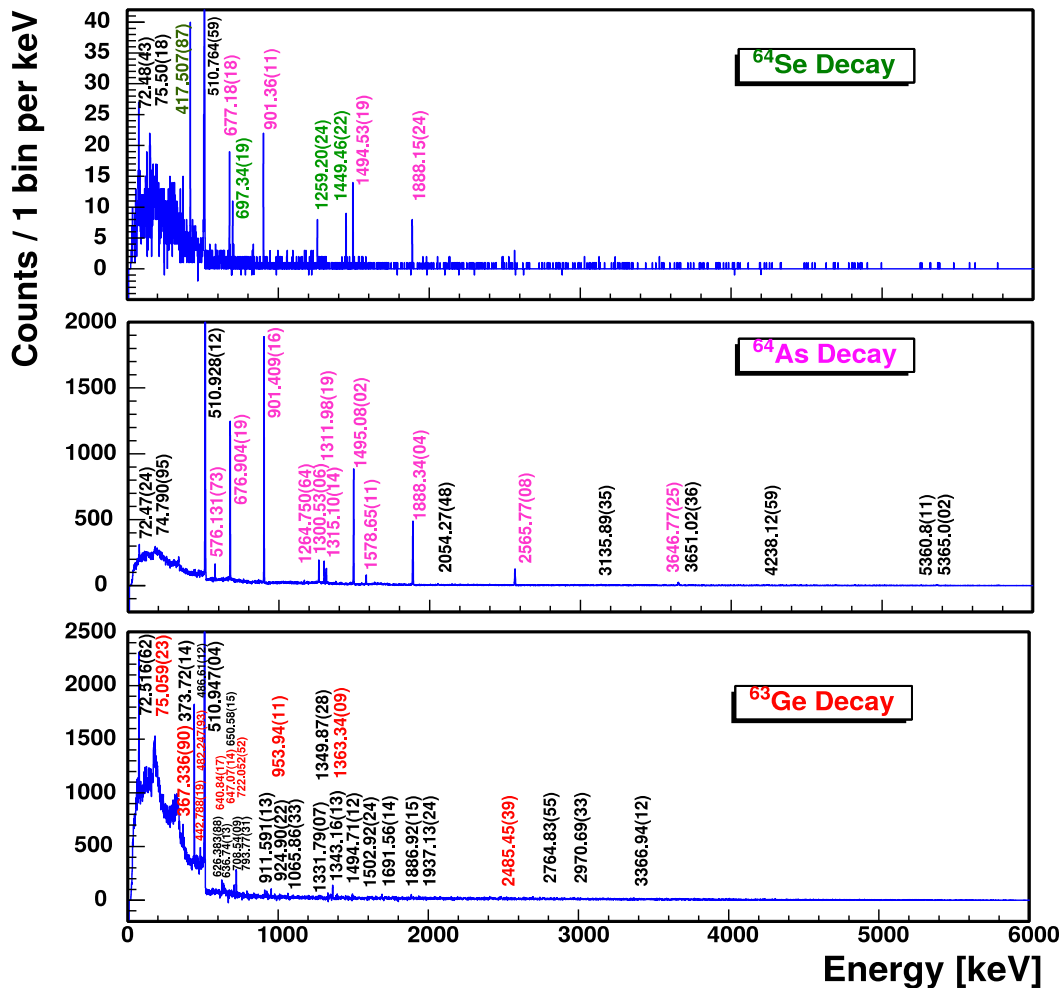


Figure 3. From top to bottom, the gamma spectra associated with the implantation of  $^{64}\text{Se}$ ,  $^{64}\text{As}$  and  $^{63}\text{Ge}$ . The correlation time windows are 170, 440 and 1050 ms respectively. They have been used to deduce the origin of the lines observed in correlation with  $^{64}\text{Se}$  implantations. Gamma energies marked in green, pink and read are assigned to the decay of  $^{64}\text{Se}$ ,  $^{64}\text{As}$  and  $^{63}\text{Ge}$  respectively.

Beta-delayed proton decay was expected to happen with high probability in the decay of  $^{64}\text{Se}$  because of the low proton separation energy and with lower probability in the decay of  $^{64}\text{As}$ . These expectations were confirmed as can be seen in the corresponding proton spectra shown in figure 4. They are constructed using time correlations between the implanted ions and the decay signals (betas and protons) detected in the same pixel defined as the crossing between one X and one Y strip. The signal below 1 MeV corresponds to the  $\Delta E$  beta signal. Peaks above 1 MeV originate from the proton decay, in general summed with the beta signal. The proton peak centroids were obtained by fitting the spectra with the simulated beta-delayed proton response using the code GEANT4. The WAS3ABi DSSSD detectors were calibrated using an electron conversion source of  $^{207}\text{Bi}$ ; thus energy shifts are expected due to the several absorption effects before the electron penetrates into the detector and to the summing of the protons with the betas. To take into account all these effects an internal calibration is essential. The energy shifts were evaluated using  $^{57}\text{Zn}$  and  $^{71}\text{Ge}$  beta-delayed proton spectra obtained in the same experiment and constructed in the same manner as the  $^{64}\text{Se}$  beta-

delayed proton spectrum. The corresponding energies were taken from [10]. The uncertainties in the proton energies shown in figure 4 originate from the fit of the response function as well as the systematic shifts of the proton energies compared with those reported in the literature [10].

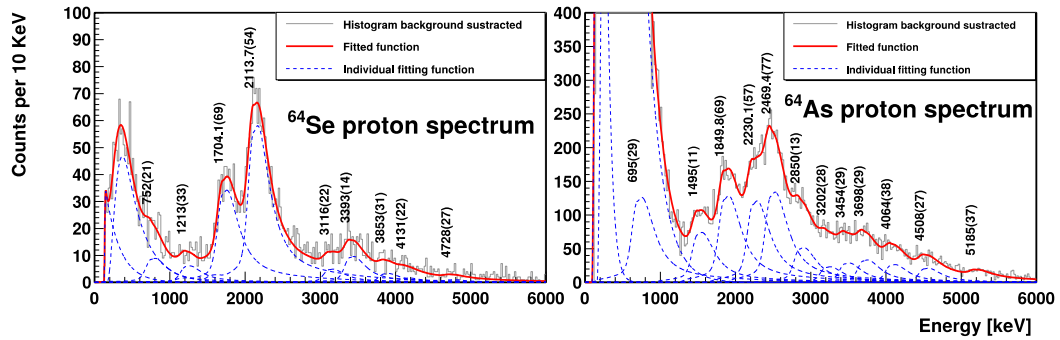


Figure 4. DSSSD spectra associated with the beta decays of  $^{64}\text{Se}$  and  $^{64}\text{As}$ . Peaks associated with beta-delayed proton decay are marked with energies.

The half-lives of the three nuclei under study are presented in figure 5. They are based on the correlations between the implanted  $^{64}\text{Se}$  and  $^{64}\text{As}$  ions and the proton decays happening before and after the implantation in the same pixel, and the implantation-beta correlations in the case of  $^{63}\text{Ge}$ .

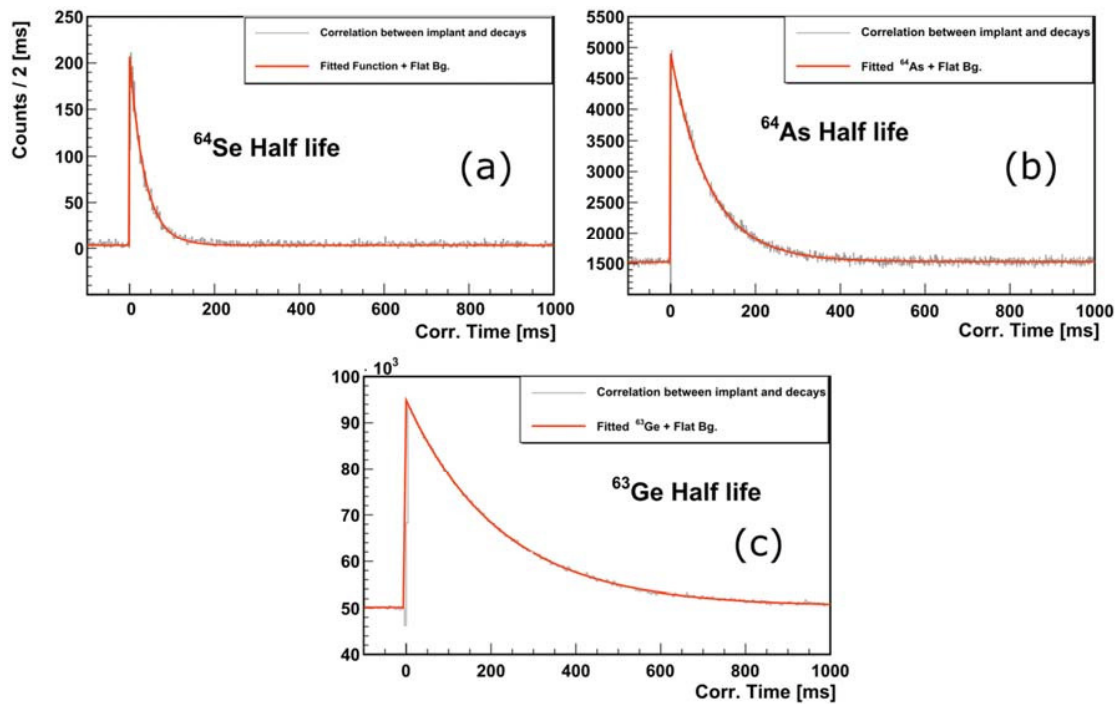


Figure 5: Fit of the implant-beta and implant-proton correlation for the half-life of (a)  $^{64}\text{Se}$ , (b)  $^{64}\text{As}$ , (c) and  $^{63}\text{Ge}$ .

Based on the analysis of all these data, including gamma–gamma as well as proton-gamma coincidences we have obtained the following preliminary level schemes:

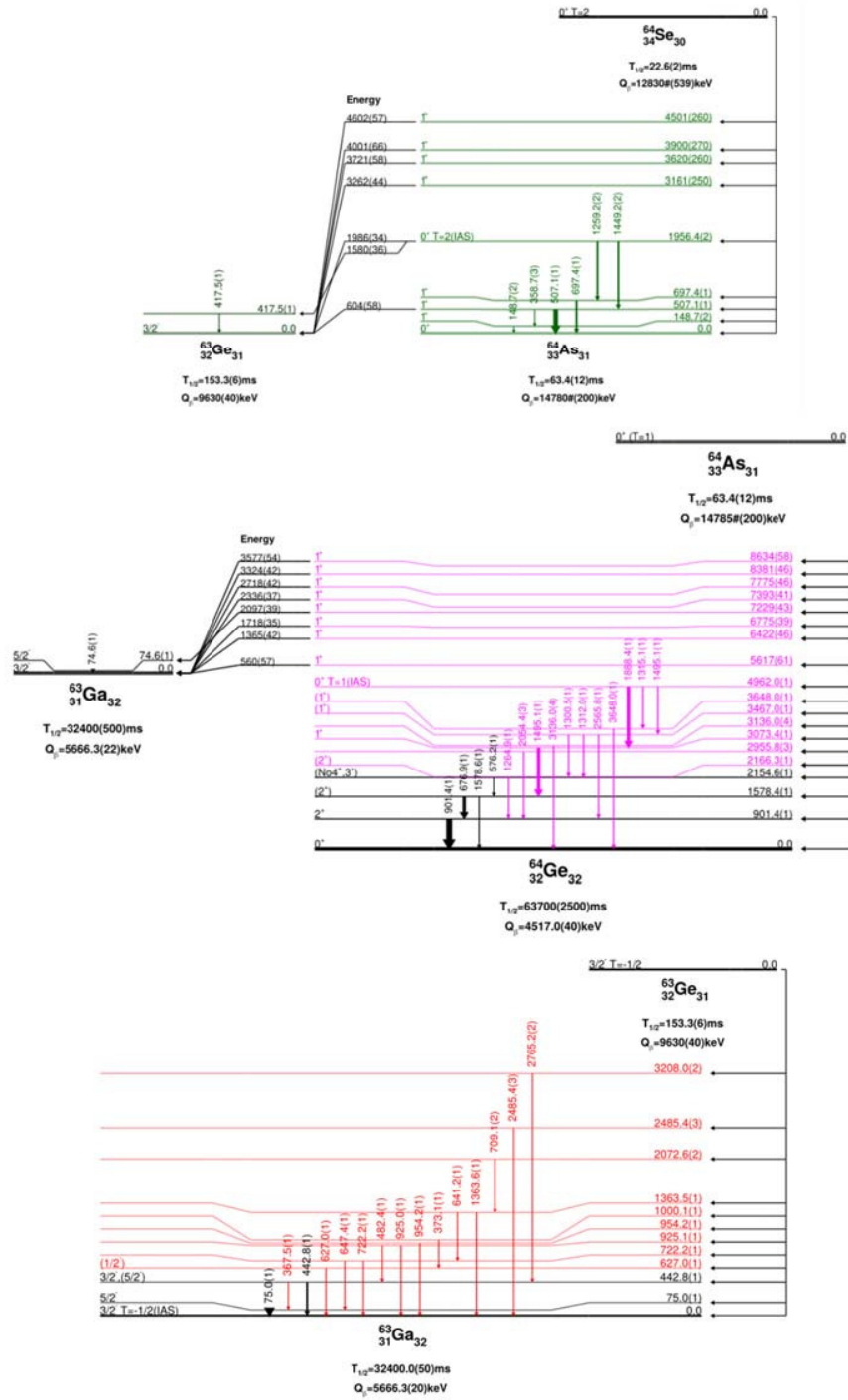




Figure 6. Decay schemes for  $^{64}\text{Se}$ ,  $^{64}\text{As}$  and  $^{63}\text{Ge}$  studied in this work. Colors represent the gamma lines observed for the first time in this work, while the ones previously reported in the literature are shown in black. In the case of  $^{64}\text{Ge}$ , they were reported in the in-beam work of Farnea et al. [12], and  $^{63}\text{Ge}$  data are from [13,14]. The Q-beta values are taken from [11].

#### 4. Discussion

As mentioned in the introduction the study of the decay of  $^{64}\text{Se}$  was one of the main goals of the present experiment. A strong population of the IAS at around 2 MeV is expected in the decay. This level is identified as the experimental level at 1955 keV energy. The IAS has isospin 2 and spin parity  $0^+$ . Although this level is well above the proton separation energy, it decays by proton emission as well as by electromagnetic transitions. This is due to the forbidden character of this proton decay since it originates from a state with  $T=2$  and populates states in  $^{63}\text{Ge}$  with (presumably) isospin  $\frac{1}{2}$ . Two gamma cascades de-excite the IAS and define its excitation energy. The direct transition from the state at 506 keV to the ground state is difficult to observe because it is obscured by the 511 keV annihilation peak. Four other states are strongly populated in the decay of  $^{64}\text{Se}$  and are consequently assigned as  $1^+$  levels. The lack of evidence of direct beta feeding from  $^{64}\text{Se}$  to the ground state of  $^{64}\text{As}$ , together with the information from the mirror nucleus of the  $0^+$  character of the  $^{64}\text{Zn}$  ground state, defines the ground state of  $^{64}\text{As}$  as  $0^+$ . Such a state is normally called the AAS (Anti Analogue State) and it is expected to have a configuration very similar to the IAS but with a different isospin.

The decay scheme of  $^{64}\text{Se}$  can be directly compared with the charge exchange reaction on the mirror stable nucleus  $^{64}\text{Zn}$  [9], the energies of the relevant levels can be compared in table 2. Good isospin symmetry is observed. A more detailed comparison of the Gamow-Teller strength BGT and Fermi strength BF is in preparation [15].

Similarly, a good isospin symmetry is observed for the  $T=1/2$  mirror pairs  $^{63}\text{Ge}$  and  $^{63}\text{Ga}$ .

Ex. $^{64}\text{As}$ (keV)	Ex. $^{64}\text{Ga}$ (keV)	Ip
0	0	$0^+$
147	127	$1^+$
506	426	$1^+$
697	666	$1^+$
1955	1923	$0^+$
Ex $^{63}\text{Ge}$ (keV)	Ex $^{63}\text{Ga}$	Ip
0	0	$3/2^-$
75	75	$5/2^-$
417	443	

Table 2: Comparison of mirror states in  $^{64}\text{As}$  and  $^{64}\text{Ga}$ , and in  $^{63}\text{Ge}$  and  $^{63}\text{Ga}$ . The excitation energies originate from the present study for  $^{64}\text{As}$ ,  $^{63}\text{Ge}$  and  $^{63}\text{Ga}$  and from [9] for  $^{64}\text{Ga}$ . As can be seen, good isospin symmetry is observed.

Finally, new excited states could be observed in the  $N=Z$  nucleus  $^{64}\text{Ge}$  populated in the decay of  $^{64}\text{As}$ . Nuclei with  $N=Z$  are particularly interesting because proton-neutron correlations are supposed to play an important role in their structure. Moreover  $N=Z$  even-even nuclei can provide information

on isospin symmetry. For instance, in  $^{64}\text{Ge}$ , a study by Farnea et al [12] using a fusion evaporation reaction revealed a forbidden E1 transition which could only be explained in terms of T=0 and T=1 mixing. In this in-beam study a number of yrast states were observed up to spin 14+. In our study, we could locate a number of low spin states, mainly 1+ states as well as the 0+ IAS of  $^{64}\text{As}$  located at 4961 keV excitation energy.

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