Eur. Phys. J. A **15**, 121–124 (2002)
DOI 10.1140/epja/i2001-10238-4

**THE EUROPEAN
PHYSICAL JOURNAL A**

Studies with one- and two-proton drip line nuclei

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Received: 21 March 2002 /

Abstract. In recent experiments at GANIL, we studied nuclei at the one- and two-proton drip line. The production rates allowed to search for direct 2p emission in the drip line nuclei ^{42}Cr, ^{45}Fe, and ^{49}Ni. No evidence for this decay mode was found in ^{42}Cr and ^{49}Ni, whereas the situation stays unclear for ^{45}Fe due to the limited statistics. In the medium-mass region ($A = 50$–70), the half-life was measured for all proton-rich nuclei in the range $T_z = 0$ to $T_z = -1$ between $Z = 27$ and $Z = 36$. First half-lives were determined for ^{60}Ga, ^{62}Ge, ^{64}As and ^{66}Se. Finally, β-decay studies of the $0^+ \rightarrow 0^+$ decay of ^{62}Ga have been performed at IGISOL in Jyväskylä. Non-analog transitions have been observed and are compared to theoretical predictions.

PACS. 27.40.+z $39 \leq A \leq 58$ – 21.10.Tg Lifetimes – 23.50.+z Decay by proton emission – 25.70.Mn Projectile and target fragmentation

1 Introduction

In recent experiment at the LISE3 separator of GANIL, we studied exotic nuclei close to the proton drip line in the mass $A = 40$–70 region. These nuclei decay by β-delayed one- or two-proton emission or, maybe, by direct two-proton decay. The study of these nuclei yields unique nuclear-structure information on proton drip line nuclei not accessible by other means.

In the present paper, we will describe results obtained in spectroscopic studies close to or at the one-proton and two-proton drip line. In the ^{48}Ni region, two-proton radioactivity is predicted to show up and ^{45}Fe, ^{48}Ni, and ^{54}Zn are the prime candidates for this decay mode. ^{42}Cr and ^{49}Ni are most likely decaying by β-delayed decay branches.

For the modeling of the astrophysical rp-process, β-decay half-lives for nuclei close to the proton drip line in the mass 50–70 region are an important input. We measured these half-lives in a recent GANIL experiment for nuclei with an isospin projection $T_z \leq 0$. These results will be presented in sect. 3 of the present paper.

Finally, the superallowed β-decay of $T = 1$ nuclei may be used to study the characteristics of the weak interaction. For this purpose, high-precision ft-values have to be calculated and then corrected for radiative and Coulomb effect. To understand discrepancies observed for lower-mass nuclei, we studied the decay of ^{62}Ga in an experiment at IGISOL in Jyväskylä. The observation of non-analog decay branches will be reported in sect. 4.

2 Decay studies for nuclei in the ^{48}Ni region

When approaching the proton drip line, the emission of two protons from a nuclear state becomes possible. This decay mode is mainly sequential if the emission of one proton to an intermediate state can occur. This process has first been observed in the β2p-decay of ^{22}Al [1].

If there is no accessible intermediate state, the sequential emission is forbidden, and the emission of the two protons is simultaneous. This situation is expected to occur from nuclear ground states. Then two cases are possible: i) the decay may proceed via a three-body desintegration as observed for ^{12}O [2] or ^{6}Be [3] or ii) the nuclear state may decay via ^{2}He emission and a strong angular and energy correlation between the two emitted protons may be expected. Up to now, this second process has never been observed experimentally. In the $A \simeq 50$ mass region, a specific interest arises for decay studies since several nuclei in this region are candidates for this correlated emission of two protons from the ground state.

Our experiments in the titanium-to-nickel region allowed not only to observe the doubly magic nucleus ^{48}Ni for the first time [4] (fig. 1), but also to determine half-lives for almost all nuclei [5] close to the proton drip line in this region. Beyond that proton-γ coincidences allowed to establish partial decay schemes for some of the nuclei [6].

Whereas, due to limited statistics, the situation is still unclear for ^{45}Fe, one of the best candidates for two-proton radioactivity, the nuclei ^{42}Cr and ^{49}Ni could be studied with sufficient accuracy and the data allow to distinguish between the two possible decay branches two-proton radioactivity and β-delayed decays.

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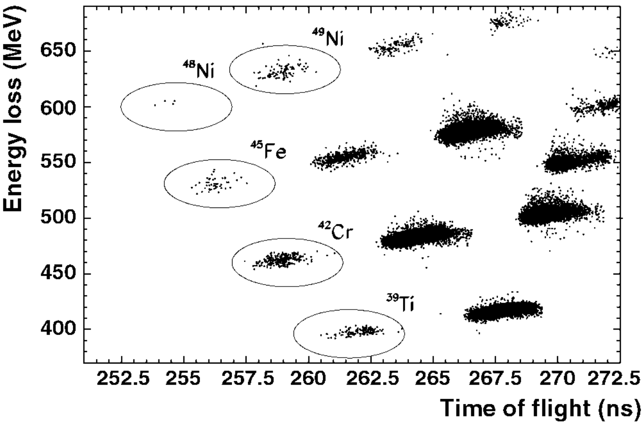

Fig. 1. First observation of ^{48}Ni from the fragmentation of an intense ^{58}Ni beam at LISE3. The time of flight is measured between the target and the detection setup, whereas the energy loss is due to the first silicon detector in a stack of five detectors.

Figure 2 shows the decay energy spectra for these two nuclei. The peaks observed at 1.9 MeV and 3.7 MeV allow to clearly identify the decay as a β-delayed branch. For two-proton radioactivity, the decay energy should be of the order of 1 MeV only.

Higher-statistics experiments are needed to study the decay of the main two-proton emission candidates ^{45}Fe, ^{48}Ni, and ^{54}Zn.

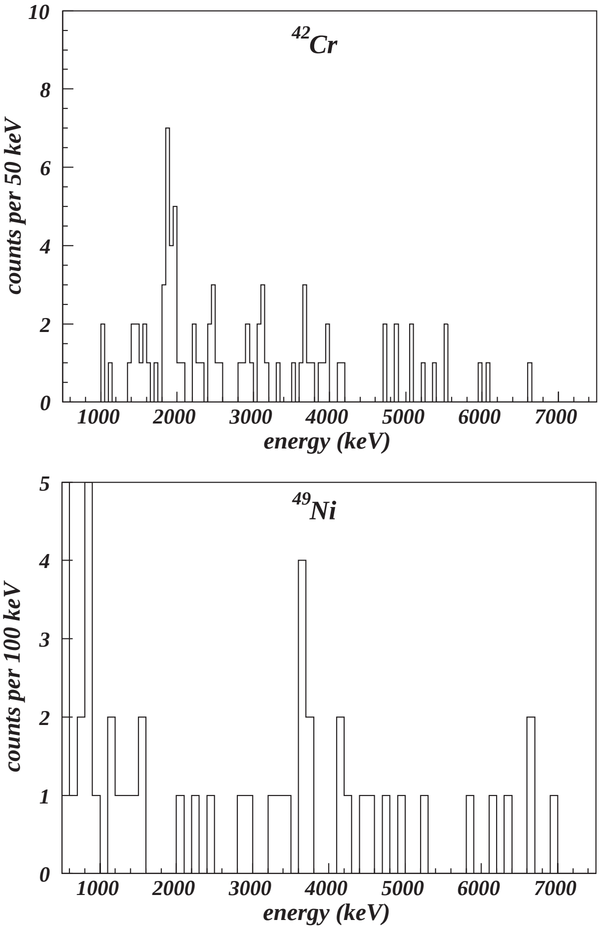

Fig. 2. Decay energy spectra for the decay of ^{42}Cr (upper panel) and ^{49}Ni (lower panel). The dominant peaks at 1.9 MeV and 3.7 MeV, respectively, are characteristic for β-delayed branches.

3 Half-life measurements of ^{78}Kr fragments

Nuclei in the region close to the proton drip line with $Z = 30$–40 are of particular interest in the nucleosynthesis. The abundance flow of the rapid proton-capture process (rp-process) on the surface of accreting neutron stars is determined mainly by the competition of proton-capture reactions and β-decays along the $N = Z$ line. This process has been proposed [7] to be able to synthesize proton-rich isotopes up to masses as large as $A = 100$. In addition, the rp-process in these systems could produce light Mo and Ru isotopes (^{92,94}Mo, ^{96,98}Ru) which might explain the large abundance of these nuclides in the solar system, the so-called P-nuclei.

If the nuclei are sufficiently bound so that their decay be dominated by β-decay, the rp-process can pass through them by proton capture and proceed to higher masses. Therefore, if one of the key nuclei is proton unbound, the rp-process ends or is at least significantly slowed down due to the rather long β-decay half-life of these waiting-point nuclei as compared to the time scale of the rp-process. This time scale is of the order of 10–100 s and is mainly determined by nuclear masses, β-decay rates of the nuclei involved and the capture cross-sections of the relevant nuclear reactions.

The β^+-decay half-lives of 23 neutron-deficient nuclei in the cobalt-to-krypton region have been measured following the fragmentation of a primary ^{78}Kr beam at an energy of 73 MeV per nucleon [8]. Ions of interest were selected by the LISE3 separator and implanted in a silicon telescope where their decay was observed.

The β^+-decay half-life of the fragments was not determined by the classical method, *i.e.* by switching the beam off after implantation of a fragment by a hardware trigger [9], but they were deduced in the following way. In the off-line analysis, cuts were applied to a two-dimensional particle identification matrix of ΔE *versus* TOF. After an implantation, subsequent β^+-decays were correlated with all previous implants in the same pixel of the silicon strip detector during a 5 s period. To obtain a β^+-decay time spectrum, the time difference between the ion implantation and any subsequent decay signal in the same pixel was determined. Uncorrelated radioactivity events contributed to a constant background level in the time spectra. The half-lives of the radioactive decays were obtained by applying a fit to the data with a function composed of an exponential decay plus a constant background level. For nuclei with short-lived daughters, the daughter decay was taken into account.

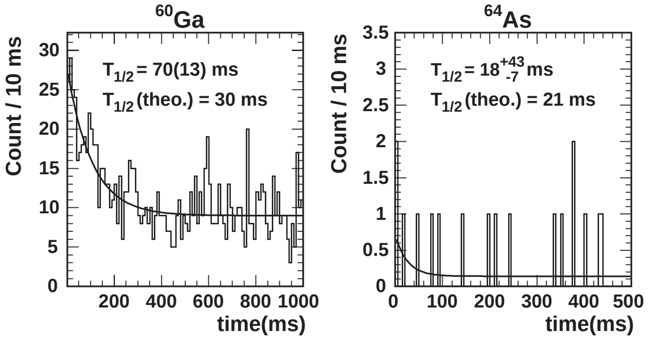

Fig. 3. Decay time spectra for the decay of ^{60}Ga (left-hand side) and ^{64}As (right-hand side). The half-lives were determined by correlating implantation of an unambigously identified fragment and its decay in the silicon detectors. The half-life of ^{60}Ga has been measured recently also at the GSI online separator [10]. The theoretical values are from the Gross theory [11].

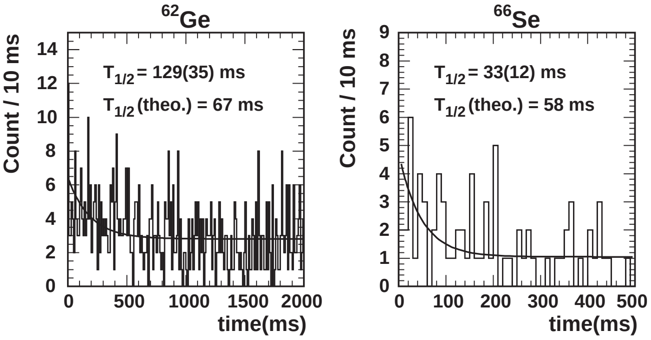

Fig. 4. Decay time spectra for the decay of ^{62}Ge (left-hand side) and ^{66}Se (right-hand side). The half-lives of these nuclei have been measured for the first time. The theoretical values are from the Gross theory [11].

The half-lives of the $T_z = -1$ nuclei ^{60}Ga, ^{62}Ge, ^{64}As and ^{66}Se are determined for the first time with values of (70 ± 13) ms, (129 ± 35) ms, 18^{+43}_{-7} ms and (33 ± 12) ms, respectively. For many other nuclei, the precision on the half-life could be improved. All our values agree very well with previous measurements within the error bars, except for ^{63}Ge where the results match only within two standard deviations.

Figure 3 shows the decay curves for ^{60}Ga and ^{64}As. These nuclei were identified as key nuclei for the rp-process. As they seem to be particle bound and decay by β-decay, the rp-process can proceed via these nuclei and go to higher masses.

In fig. 4, we show our new results on ^{62}Ge and ^{66}Se. Table 1 gives our experimental results for the half-lives of the 23 nuclei.

Table 1. Summary of half-life values for isotopes with $T_z \leq 0$ between $Z = 27$ and $Z = 36$.

Nucleus	T_z	Present work (ms)
^{54}Co	0	172 ± 23
^{62}Ga	0	114 ± 2
^{66}As	0	97 ± 2
^{70}Br	0	79 ± 36
^{53}Co	$-1/2$	240 ± 10
^{55}Ni	$-1/2$	196 ± 5
^{57}Cu	$-1/2$	183 ± 17
^{59}Zn	$-1/2$	173 ± 14
^{61}Ga	$-1/2$	148 ± 19
^{63}Ge	$-1/2$	150 ± 9
^{65}As	$-1/2$	126 ± 16
^{67}Se	$-1/2$	136 ± 12
^{71}Kr	$-1/2$	83 ± 48
^{54}Ni	-1	103 ± 9
^{56}Cu	-1	82 ± 9
^{58}Zn	-1	83 ± 10
^{60}Ga	-1	70 ± 13
^{62}Ge	-1	129 ± 35
^{64}As	-1	18^{+43}_{-7}
^{66}Se	-1	33 ± 12
^{70}Kr	-1	42 ± 31
^{57}Zn	$-3/2$	37 ± 5
^{61}Ge	$-3/2$	36 ± 21

4 Non-analog decay branches in the decay of ^{62}Ga

The electroweak part of the standard model can be tested via the determination of corrected ft-values, the so-called $\mathcal{F}t$-values. They are obtained by half-life, β^+-decay branching ratio and Q_β measurements with high accuracy. Hardy *et al.* [12] used the superallowed $0^+ \to 0^+$ Fermi transitions of nuclei from ^{10}C up to ^{54}Co to test the standard model via the Conserved Vector Current (CVC) hypothesis. This hypothesis seems to be fullfilled at a level of several 10^{-4} [12,13]. From these $\mathcal{F}t$-values, the V_{ud} matrix element of the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix can be deduced. The standard model states that this matrix should be unitary. However, according to our present knowledge, the unitarity of the CKM matrix is not fullfilled at the 2.5 σ level.

For these studies, the extracted ft-values must be corrected for radiative and Coulomb effects, calculated using various theoretical approaches [14–16]. While these corrections are generally in good agreement with each other for nuclei where experimental data are available, there are considerable differences between the predictions for heavier nuclei. To a large extent, precise measurements of ft-values for Fermi superallowed β-decays in heavier nuclei (with $T = 1$) coupled with the previous results will enable us to test the different predictions.

We started a program to measure the decay of ^{62}Ga at IGISOL in Jyväskylä. ^{62}Ga is produced by ^{64}Zn(p, 3n)^{62}Ga fusion-evaporation reactions at about 48 MeV. Residues are thermalized in a He chamber before being extracted, selected in a magnetic dipole and stopped on a tape system in the detection device.

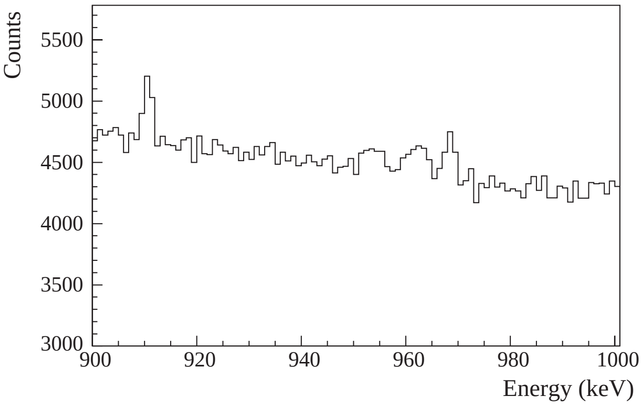

Fig. 5. γ-ray spectrum from the decay of ^{62}Ga. The peak at 954 keV comes from the decay of the first excited 2^+ state in the daughter nucleus ^{62}Zn. The branching ratio is 0.12(3)%.

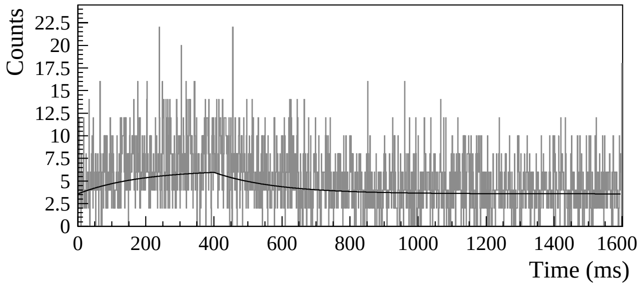

Fig. 6. Decay time spectrum for the peak at 954 keV. The fit of the half-life of 127(13) ms is in agreement with the known half-life of ^{62}Ga of 116 ms.

The detection system consists of a cylindrical plastic scintillator for β detection and three high-efficiency germanium detectors for γ detection in close geometry around the implantation point.

Figure 5 shows the γ-spectrum in the region of the 954 keV peak, the decay of the excited 2^+ state in the daughter nucleus ^{62}Zn. From the number of implanted nuclei, the detection efficiency, and the number of counts in the 954 keV line, we deduce a branching ratio for this γ line of 0.12(3)% yielding an upper limit for the branching ratio of the superallowed Fermi decay of ^{62}Ga of 99.88(3)%. As shown in fig. 6, this γ line decays with the known half-life of ^{62}Ga of about 116 ms.

The decay of the excited 0^+ state via the 2^+ state has not been observed. We deduce an upper limit for this decay sequence of 0.017%. From this non-observation we determine an upper limit for the isospin-mixing matrix element of $\delta_{\mathrm{IM}} < 0.093$. This value can be compared to predictions of Ormand and Brown [15] of 0.169 and 0.079 depending on the effective fp-shell interaction used.

A possible Gamow-Teller fed state is observed by a decay sequence of a 2225 keV γ-ray in coincidence with the 954 keV line.

5 Future perspectives

New experiments with slightly increased statistics mainly due to an improved setup will allow us to study the decays of ^{45}Fe and ^{54}Zn which will be produced with counting rates of 10–20 isotopes per day. For ^{48}Ni with about one count per day, a detailed study has to await improved production rates or higher-transmission separators.

Concerning the modeling of the rp-process, studies are on the way to investigate the influence of our new half-lives on stellar evolutions in rp-process networks.

New higher-intensity measurements of the decay of ^{62}Ga are planned at IGISOL. In particular, the use of a purification trap should allow us to increase significantly our precision of the branching ratios and on the half-life of this nucleus.

The experimental data presented here were obtained in very fruitful collaboration with colleagues from CEN Bordeaux-Gradignan, GANIL Caen, University of Warsaw, IAP Bucarest, IReS Strasbourg, FLNR Dubna, University of Surrey and JYFL Jyväskylä.

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