Spin-flip $\beta^-$ decay of even-even deformed nuclei $^{110}$Ru and $^{112}$Ru*

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Neutron-rich nuclides $^{110}$Ru and $^{112}$Ru produced in symmetric fission of $^{238}$U by 20 MeV protons have been studied at the IGISOL facility by means of $\beta$-ray, $\gamma$-ray and conversion electron spectroscopy. A total of 12 and 6 $\gamma$-transitions were observed in the decays of $^{110}$Ru and $^{112}$Ru, respectively. Multipolarities were determined for a few transitions. The beta decay half-life was determined to be $11.6 \pm 0.6$ s for $^{110}$Ru and $1.75 \pm 0.07$ s for $^{112}$Ru. As a side product, a new value of $2.1 \pm 0.3$ s for the $\beta$ half-life of the $^{112}$Rh $1^+$ state was obtained. The decay energy measured with the plastic scintillator was $2.81 \pm 0.05$ MeV for $^{110}$Ru and $4.52 \pm 0.08$ MeV for $^{112}$Ru.

The beta decay schemes of $^{110}$Ru and $^{112}$Ru isotopes indicate that the main fraction of their beta strength resides in two $0^+ \rightarrow 1^+$ spin-flip transitions with their log $f$ values between 4.4 and 4.7. The decay energies and the energies of the $1^+$ GT states are compared with the macroscopic-microscopic model calculations. The observed GT-strengths are discussed in the framework of the deformed single-particle model.

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1. Introduction

Experiments on beta decay of exotic nuclei far from the valley of beta-stability are a rich source of information both for studies of nuclear structure and for studies of many interesting applications such as heavy element synthesis in stellar environments and double beta decay. A full understanding of the mechanism of the beta decay is of great importance in all these fields. The focus in the present work is on the study of the distribution and the magnitude of $\beta$-strength in decay of neutron-rich nuclei as a function of deformation in the region between the nearly spherical $Z = 50$ (Sn) and the strongly deformed $Z = 40$ (Zr) nuclei.

The studied mass region is one of the few areas on the neutron-rich side of the nuclear chart where fast $\beta^-$ transitions to low-lying states are expected to occur between the spin partner shell model orbits. To first order in spherical approximation only one Gamow Teller (GT) transition, $|0^+\rangle \rightarrow |g_9/2^+_\pi g_9/2^+1^+\rangle$ is possible. Due to nuclear deformation spherical single-particle states are split to Nilsson states labeled by the asymptotic quantum numbers $K^\pi[N, n_s, \Lambda]$. The spin-flip transitions obeying the (additional) asymptotic quantum number selection rules: $\Delta K = 1, \Delta N = 0, \Delta n_s = 0$ and $\Delta \Lambda = 0$ in the single-particle model ($I = \Omega = K$) are called allowed unhindered (au) and can be identified by their low log $f$ values. These transitions form a distinct category with log $f \leq 5$, see [1, 2].

As a first step we have chosen to study the decay of even-even nuclei, because they provide a unique assignment for the parent state, avoiding the difficulty of unknown spin-parity, commonly related with the spectroscopy of nuclei far from stability. In the earlier experiments on $^{114, 116, 118}$Pd isotopes [3] the total GT-strength was found to be quenched to 12, 22 and 29% as compared with the spherical proton-neutron quasi-particle random-phase approximation (pQRPA) estimates [4], respectively. Moreover the GT-strength was found to be concentrated in two to four $1^+$ states. The studied Pd isotopes and their daughter nuclides are known to be relatively softly (weakly) deformed, with different shapes competing at low excitation energies, even for the $1^+$ states. Thus, it is of great interest to extend these studies to the decays of neutron-rich Ru isotopes, which are expected to have more pronounced deformed shapes. Details of the level structure of the two Ru isotopes, $^{110}$Ru and $^{112}$Ru, has recently been studied through the beta decay of $^{110}$Tc and $^{112}$Tc isotopes [5].

In this work the decays of neutron-rich $^{110}$Ru and $^{112}$Ru isotopes were studied by using the on-line isotope separator IGISOL [6] and the symmetric fission of $^{238}$U.

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The heaviest Ru isotope, whose decay has been published up to now is $^{113}\text{Ru}$ [7]. Preliminary observation of an even more neutron-rich isotope, $^{114}\text{Ru}$, has been reported in [8].

2. Experimental techniques

The experiments were performed using the MC-20 cyclotron and the IGISOL on-line mass separator facility located at the Department of Physics of the University of Jyväskylä [6]. Fission fragments from four natural uranium targets, bombarded with 20 MeV protons, were thermalized by helium as singly charged ions and transported by the ion guide technique into an isotope separator. Chemical nonselectivity and short delay time ($\approx$ ms) allow separation of very neutron-rich nuclei of all elements with nearly constant efficiency. For example, typical intensities of the order of a few times $10^3$ ions/s per isobar are obtained for highly refractory elements from Zr up to Rh with the proton beam intensity of 1 mA. The neutron-rich isotopes of these elements are produced by the symmetric mode of fission. The production rates of the studied nuclides $^{110}\text{Ru}$ and $^{112}\text{Ru}$ were about $3 \cdot 10^2$ atoms/µC.

In allowed $\beta^-$ decay the reduced GT transition strength is connected with the experimental observables via the expression, $B(\text{GT}) = 3662/\tau f$, where $f$ is the phase space factor and $\tau$ is the partial half-life in seconds and the constant 3862 s comes from the constant $D = 6160$ divided by a square of a free-nucleon value of a ratio of the axial to vector coupling constants $(g_A/g_V) = 1.263$ [9]. The determination of $B(\text{GT})$ involves a measurement of the half-life, the decay energy, the determination of the level scheme of the daughter nucleus and the beta feeding pattern.

Beta decay energies were determined with a $\Delta E - E$ telescope detector system operating in coincidence with 25% and 20% Ge(HP) detectors, as described in [5]. The detector telescope consists of a 300 mm$^2$ in area and 0.5 mm thick Si(Au) surface barrier $\Delta E$ detector and a 60 mm thick and 75 mm in diameter plastic scintillator (BC-400) E detector. The endpoint energies were obtained by applying a shape fitting procedure to the beta spectra [10] instead of the traditional Fermi-Kurie analysis. In this way the complicated procedure to remove the effects of the response function of the detector was avoided. The method is based on the availability of a good set of single component calibration activities produced in reasonable yields at IGISOL. The set of the calibration activities included $^{99}\text{Nb}$, $^{99}\text{Y}$, $^{125}\text{Sn}$, $^{125}\text{In}$ and $^{137}\text{Xe}$, which provided endpoint energies from 2 to 7 MeV [11, 12, 13].

Although, for simplicity the even-even beta-decaying nuclei were selected for this study, their decay to odd-odd daughters often result in complex decay schemes, whose determination requires as complete a spectroscopic approach as possible. A set of experiments to acquire the information needed for the construction of the decay schemes were performed by using the 20% and 25% co-

axial Ge detectors as well as the 1.4 cm$^3$ planar Ge detector.

In addition to the standard spectroscopic methods, we have utilized a novel magnetic lens type conversion electron spectrometer, ELLI, which can be used at the collection point to measure implanted sources directly with high efficiency and low background behind the IGISOL-system [14]. It can also be operated in coincidence mode together with the previously mentioned Ge and Si(Au) detectors to obtain X-ray, $\beta$ and $\gamma$-gated conversion electron spectra.

$\beta$ decay half-lives were determined by using the pulsed beam technique. The beam of the separated radioisotopes was vertically deflected for the decay time measurements. Simultaneously the cyclotron beam was switched off to reduce the effects of the neutron-induced background. The collection tape was moved in the beginning of each beam-on period. Typically, the data stored in the event mode on magnetic tape included $\beta$, $\gamma$ and $e^-$-energies, fast timing signals as well as the time of occurrence of each event.

3. Experimental results

Prior to investigation only a limited amount of experimental information on the studied Ru nuclides was available. The half-life of $^{110}\text{Ru}$ had been reported to be as 14.6 $\pm$ 1.0 s as a weighted mean of several radiochemical measurements [15]. Two gamma-rays with energies of 112.1 and 95.8 keV had also been reported to belong to the $^{110}\text{Ru}$ decay [16]. No direct observation of the beta decay characteristics of $^{112}\text{Ru}$ had been made. In a radiochemical study [16] a half-life of 3.6 s for $^{112}\text{Ru}$ was indirectly obtained, but it was later found to be related with the beta decay of the $1^+$ state of $^{111}\text{Rh}$ [17]. The recently reported half-life of 1.75 $\pm$ 0.7 s for $^{112}\text{Ru}$ based on the time decay of the 327.0 keV $\gamma$-ray was measured at the IGISOL-facility [7].

3.1. Spectroscopic data

$^{110}\text{Ru}$. Beta-gated gamma spectra corresponding to activities observed at mass numbers $A = 110$ and 112 at the focal point of the IGISOL-system are shown in Fig. 1. The upper spectrum, taken in coincidence with 0–2.8 MeV $\beta$-rays, displays several gamma-transitions assigned to the beta decay of $^{110}\text{Ru}$ through their $K$-X-ray, $\gamma$-ray and $\beta$-ray coincidence relations. The other $\gamma$-lines are marked according to their beta-parent nucleus. The time dependence of the intensity of the 112 keV $\gamma$-line yields a half-life of $T_{1/2} = 11.6 \pm 6$ s for $^{110}\text{Ru}$, see Fig. 2.

The energies and relative intensities of the $\gamma$-transitions following the decay of $^{110}\text{Ru}$ are given in Table 1. The information in Table 1 on coincidence relations is based on studies using either two Ge($\gamma$) detectors or one Ge($\gamma$) detector combined with a Ge($\gamma/X$) one. A $K$-conversion coefficient value, $\alpha_K = 0.19 \pm 0.04$, for the 112 keV transition was obtained from the conversion electron data and a value $\alpha_K = 0.22 \pm 0.15$ from the co-