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α decay of the $\pi h_{11/2}$ isomer in ^{164}Ir

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The α-decay branch of the $\pi h_{11/2}$ isomer in ^{164}Ir has been identified using the GREAT spectrometer. The ^{164}Ir nuclei were produced using the ^{92}Mo(^{78}Kr, $p5n$)^{164}Ir reaction and separated in flight using the recoil ion transport unit (RITU) gas-filled separator. The measured α-decay energy of 6880 ± 10 keV allowed the excitation of the $\pi h_{11/2}$ state in ^{160}Re to be deduced as 166 ± 14 keV. The half-life of ^{164}Ir was measured with improved precision to be 70 ± 10 μs and an α-decay branching ratio of $4 \pm 2\%$ was determined. Improved half-life and branching ratio measurements were also obtained for ^{165}Ir, but no evidence was found for the ground-state decays of either ^{164}Ir or ^{165}Ir.

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I. INTRODUCTION

Alpha radioactivity is the principal decay mode of neutron-deficient isotopes of elements from $_{82}$Pb to $_{94}$Pu. Below $Z = 82$, α radioactivity is still dominant for even-Z elements down to $_{76}$Os, although proton emission dominates for the lightest known isotopes of the odd-Z elements. One feature of proton emitters with $N \geqslant 84$ is that most of the proton-emitting states also have a competing α-decay branch [1]. A typical example is $^{170}_{79}$Au, in which proton and α-particle emission have been observed from both the ground state and a low-lying isomeric state [2,3]. Measurements of the proton-decay energies, half-lives, and branching ratios indicate that the protons are emitted from $\pi d_{3/2}$ and $\pi h_{11/2}$ orbitals, respectively. As in other odd-odd nuclei in this region, in both states the odd proton is assumed to be coupled to a neutron in a $\nu f_{7/2}$ orbital [3]. The unhindered α decays from these states populate corresponding levels in $^{166}_{77}$Ir, which also undergo both proton and α-particle emission [4].

In contrast, in the previous studies of ^{164}Ir, the lightest known iridium isotope, only proton emission from a $\pi h_{11/2}$ state was observed [2,5]. The α decay of this state would be expected to populate the $\pi h_{11/2}$ state in ^{160}Re, which is unique in this region because, instead of decaying by proton or α-particle emission, it is observed to γ decay with a half-life of 2.8 μs to the $\pi d_{3/2}$ ground state [6–8]. The γ-ray cascade identified from the decay of this $\pi h_{11/2}$ isomer comprises a 96 keV $E2$ transition followed by a 38 keV $E1$ transition. However, other unobserved transitions might be expected to form part of this cascade since the excitation energy of the isomer has been estimated from systematics to be 185 ± 21 keV [9]. By using this estimate, partial half-lives for proton and α-particle emission can be predicted, and these values are significantly longer than that observed from the γ decay of the state. However, half-lives for these decay modes vary rapidly with Q value, so it is desirable to determine the excitation energy of this state experimentally.

One method to establish the excitation energy of the $\pi h_{11/2}$ state in ^{160}Re would be through a measurement of the Q value of the α decay of the $\pi h_{11/2}$ state ^{164}Ir (see Fig. 1). The Q value for this α decay has been estimated from systematics [9], from which a branching ratio of $\sim$8% could be expected. Such a low α-decay branch would have been below the sensitivity limits of the previous studies of ^{164}Ir, in which proton-decay yields of only $\sim$five events [2] and $\sim$eight events [5] were obtained.

The Q values for decays from the $\pi d_{3/2}$ ground state of ^{164}Ir can also be estimated from systematics. These suggest that it will predominantly decay by proton emission with a half-life of ~ 1 μs. Half-lives this short can be problematic for conventional readout systems based on analog electronics, such as those used in the previous studies, but should be within the capabilities of digital readout systems which have proved capable of analyzing signals in double-sided silicon strip detectors (DSSDs) separated in time by as little as 200 ns [10]. However, the fusion-evaporation reactions used to produce proton emitters in this region generally favor the population of $\pi h_{11/2}$ states, so the $\pi d_{3/2}$ ground state of ^{164}Ir may be too weakly populated to be observed.

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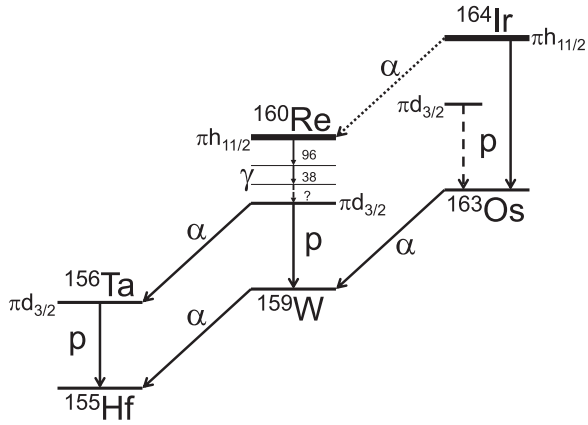


FIG. 1. Schematic diagram showing the expected proton and α decays of states in ^{164}Ir. The odd neutrons in ^{156}Ta, ^{160}Re, and ^{164}Ir are proposed to occupy $\nu f_{7/2}$ orbitals [4,5]. The discovery of the α decay of the $\pi h_{11/2}$ isomer in ^{164}Ir shown by the dotted line is presented in this work, but no evidence could be found for the proton decay of the $\pi d_{3/2}$ ground state indicated by the dashed line.

In the present work, the α-decay branch of the $\pi h_{11/2}$ state in ^{164}Ir has been identified and its proton-decay properties have been determined with improved precision. A search has been performed for the proton decay of the $\pi d_{3/2}$ ground state of ^{164}Ir. Improved half-life and branching-ratio measurements were also obtained for the $\pi h_{11/2}$ state in ^{165}Ir.

II. EXPERIMENTAL DETAILS

The experiment was performed at the Accelerator Laboratory of the University of Jyväskylä. The ^{164}Ir nuclei were produced in the fusion-evaporation reaction ^{92}Mo(^{78}Kr, $p5n$)^{164}Ir. The ^{78}Kr beam provided by the K130 cyclotron bombarded the isotopically enriched, self-supporting ^{92}Mo target foil of thickness 500 μm/cm^2. Beam energies at the front of the target of 428, 435, and 450 MeV were used for periods of 21, 18, and 270 hours, respectively. The average beam intensity was 10 particle nA.

The ^{164}Ir ions recoiled out of the target and were transported using the gas-filled separator recoil ion transport unit (RITU) [11,12] to the GREAT spectrometer [13] situated at its focal plane. The flight time was estimated to be $\sim$0.3 μs. The ions passed through a multiwire proportional counter (MWPC) and were implanted into one of two adjacently mounted DSSDs. The energy-loss signal in the MWPC and the time of flight between the MWPC and the DSSDs allowed evaporation residues to be distinguished from beam-like particles.

Both of the DSSDs had an active area of 60 mm $\times$ 40 mm and were 300 μm thick. The strips on their front and back surfaces were orthogonal and the strip pitch of 1 mm on both faces provided 4800 independent pixels. The 120 strips on the front face of the DSSDs were instrumented with the standard analog electronics, with the shaping times on the amplifiers reduced to their minimum value of 0.5 μs. Even so, the dead time for extracting energy information from successive signals in a given strip was 7 μs, which would have been too long to allow for a meaningful search for the decay of the ground state of ^{164}Ir to be attempted. Therefore, the 80 strips on the rear face of the DSSDs were instrumented with 16-channel, 14-bit Lyrtech VHS-ADC16 digital electronics modules, which had a sampling frequency of 100 MHz. Traces of length 10 μs representing the electronic response to signals in these strips were recorded, allowing energy and timing information for short-lived decays to be extracted. These data were correlated with information on pileup recorded simultaneously from the strips on the front face, in order to identify traces which may have included a fast decay and to assign these traces to a specific DSSD pixel.

An array of 28 silicon PIN diodes was mounted around the perimeter of the DSSDs in a box-like arrangement. Each PIN diode had an active area of 28 $\times$ 28 mm^2 and a thickness of 500 μm. The PIN diodes were used to measure the energies of α particles emitted in the upstream direction that escaped from the DSSDs without depositing their full energy. These escaping α particles form a background in the region of the DSSD energy spectrum where proton-decay peaks are expected. By vetoing energy signals in the DSSDs that are coincident with signals in the PIN diodes, this background can be suppressed.

A planar double-sided germanium strip detector was mounted a few mm behind the DSSDs inside the same vacuum enclosure to measure the energies of x rays and low-energy γ rays emitted during decay processes in the DSSDs. The energies of higher-energy γ rays were measured using a clover germanium detector mounted outside the vacuum chamber above the DSSDs.

All detector signals were passed to the triggerless data acquisition system [14], where they were time stamped with a precision of 10 ns. The data were analyzed using the GRAIN [15] software package, which was also used to identify traces attributed to proton decays of ^{164}Ir through correlations with subsequent ^{163}Os α decays.

III. RESULTS

The data were analyzed to obtain improved measurements of the proton decay of the $\pi h_{11/2}$ state of ^{164}Ir and to search for its α-decay branch. Figure 2(a) shows the energy spectrum of radioactive decays observed in the DSSDs within 0.5 ms of the implantation of an evaporation residue in the same pixel. The known proton-decay peaks from ^{160,161}Re and ^{164,165}Ir are visible in this spectrum above the background from α particles that escape from the DSSDs without depositing their full energy. In order to isolate the ^{164}Ir proton decays, correlations with the α decay of its daughter ^{163}Os were performed. Figure 2(b) shows events that occurred within 350 μs of an ion implantation and were followed in the same DSSD pixel within 28 ms by a ^{163}Os α decay ($E_\alpha = 6502 \pm 5$ keV, $t_{1/2} = 5.9 \pm 0.6$ ms [3,16–18]). The ^{164}Ir proton-decay peak can clearly be seen at an energy of 1814 ± 6 keV, which is in good agreement with the previous measurements of 1817 ± 8 keV [5] and 1807 ± 14 keV [2]. The energy calibration for proton-decay lines was based on the proton decays of ^{160,161}Re [7,16,19] and ^{165}Ir [4]. The yield of approximately 100 ^{164}Ir proton-decay events obtained in the present work allowed the half-life to be determined with improved precision. A half-life of 70 ± 10 μs was obtained by using the method of maximum likelihood [20].

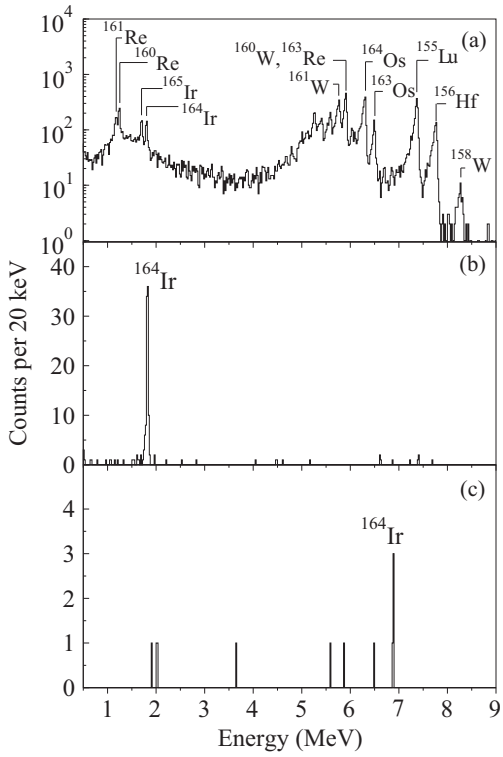


FIG. 2. (a) Energy spectrum of decay events occurring within 0.5 ms of an ion being implanted into the same DSSD pixel. (b) Energy spectrum of these events that are followed within 28 ms by an α decay of ^{163}Os. (c) Energy spectrum of decay events that occur within 0.35 ms of an ion implantation and are followed within 3 ms by a daughter energy characteristic of ^{160}Re ground-state proton decays. Escaping α particles detected in the array of PIN diodes are not included in these spectra.

Figure 2(c) shows the energy spectrum of decay events that occur within 350 μs of an ion implantation and are followed within 3 ms by a ground-state proton decay of ^{160}Re [7]. A peak comprising four counts can be seen at an energy of 6880 ± 10 keV. Two of these recoil-alpha-proton decay chains were followed by ^{159}W α decays where the full energy was deposited in the DSSD, confirming the assignment of this new α radioactivity as a decay branch from ^{164}Ir. The half-life determined for the four events using the method of maximum likelihood was $69\ ^{+41}_{-29}$ μs. This is an order of magnitude shorter than would be expected for a state decaying by α-particle emission alone but is consistent with the value measured for proton emission from the $\pi h_{11/2}$ state in ^{164}Ir. This activity is therefore assigned as the α-decay branch of the $\pi h_{11/2}$ state in ^{164}Ir.

This α decay of ^{164}Ir is expected to populate the $\pi h_{11/2}$ state in ^{160}Re, which undergoes electromagnetic decay to the $\pi d_{3/2}$ ground state with a half-life of 2.8 μs [6–8]. Electron conversion of the transitions could lead to summing with the α-particle energy signals within the analog amplifier shaping time. The effect of this summing was investigated through Monte Carlo simulations of the response of the DSSDs and electronics, using internal conversion coefficients from Ref. [21]. The simulations indicated that ~25% of the α-decay intensity would be shifted to higher energies. Given the low statistics, the observation of four events close in energy, with none shifted to higher energies as a result of summing, is consistent with this expectation.

The observed ^{164}Ir α-decay yield corresponds to a branching ratio of $4 \pm 2\%$, after correcting for the fraction of protons and α particles that escaped from the DSSDs without depositing their full energy. A cross section of ~4 nb was estimated for the population of the $\pi h_{11/2}$ state in ^{164}Ir from the combined yield of both its decay branches. This cross section estimate assumes that 30% of all ^{164}Ir nuclei produced were implanted into the DSSDs [22].

A search for proton decays of the $\pi d_{3/2}$ ground state of ^{164}Ir was performed by analyzing traces correlated with events characteristic of ^{163}Os α decays. However, no evidence for the proton decay of this state was found. Possible explanations for this nonobservation could be that the half-life may have been too short (<0.5 μs), the yield too low (<50 pb), or a combination of these effects.

The present data were also analyzed to obtain improved measurements of the decays of the $\pi h_{11/2}$ state in ^{165}Ir, which was previously reported to have a half-life of 300 ± 60 μs and to decay by both proton and α-particle emission [4]. The upper panels of Fig. 3 show sections of a decay correlation matrix in which the decay energy of implanted nuclei is plotted against the decay energy of the daughter nuclei, while the lower panels show the projections of these matrix sections, in which both the proton- and α-decay branches of ^{165}Ir can be seen. In total, 270 ^{165}Ir proton decays were correlated with ^{164}Os α decays and 35 α decays were correlated with α decays of the $\pi h_{11/2}$ state in ^{161}Re. However, no correlations were observed of ^{165}Ir

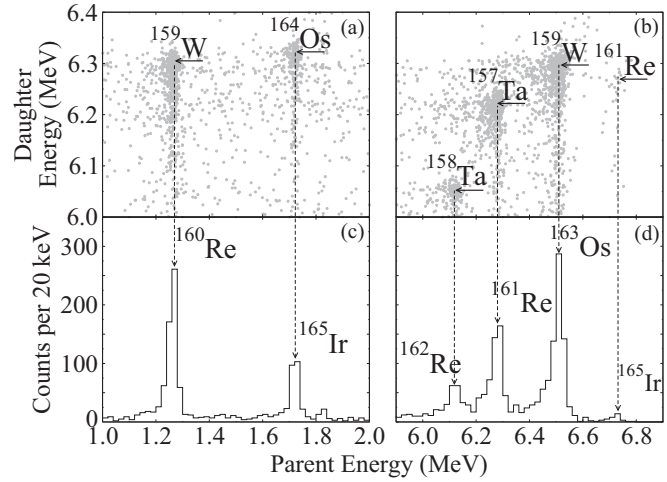


FIG. 3. (a) A section of a parent-daughter decay correlation matrix showing the correlations between proton decays of ^{160}Re and ^{165}Ir with the α decays of their respective daughters, ^{159}W and ^{164}Os. The maximum time intervals between the implantation and parent decay and between the parent and daughter decays were 1 ms and 63 ms, respectively. (b) A section of the same decay correlation matrix featuring the α decays of ^{165}Ir correlated with those of its daughter ^{161}Re. Correlations of ^{163}Os-^{159}W, ^{161}Re-^{157}Ta, and ^{162}Re-^{158}Ta are also visible. Panels (c) and (d) are projections of panels (a) and (b) showing the energies of the parent decays.

α decays with proton decays of ^{161}Re, for which the branching ratio is only a few percent [19,23]. Correcting for the daughter branching ratios [19,23,24], the α-decay branching ratio of ^{165}Ir was measured to be $12 \pm 2\%$. A half-life of 340 ± 40 μs was measured using the method of maximum likelihood, which agrees with the previously measured value [4]. No evidence was found for the decay of the ground state of ^{165}Ir.

IV. DISCUSSION

The measured α-decay energy for ^{164}Ir corresponds to a Q value of 7052 ± 10 keV. This value is shown in Fig. 4, in which the α-decay Q values of $\pi h_{11/2}$ states of odd-Z elements are plotted as a function of neutron number, together with those of the ground states of even-Z elements. The value for ^{164}Ir continues the nearly linear trend observed for lighter Ir isotopes, which is similar to that exhibited by the chain of Pt isotopes, whereas the light Os isotopes show a slight odd-even staggering in their Q values.

The Q values measured for the proton- and α-decay branches of ^{164}Ir in the present work can be combined with known Q values to calculate the excitation energy and the proton- and α-decay Q values of the $\pi h_{11/2}$ state in ^{160}Re (see Fig. 1). An excitation energy of 166 ± 14 keV was determined for the $\pi h_{11/2}$ isomer in ^{160}Re, while the Q values deduced for proton and α-particle emission were 1438 ± 12 keV and 6761 ± 16 keV, respectively. Both of these Q values are consistent with those estimated in Ref. [9], where partial half-lives of $\sim$10 ms and $\sim$1 ms were predicted for proton emission and α-particle emission, respectively. Neither of these decay modes is therefore able to compete effectively with the observed γ-decay branch from this 2.8 μs isomer. Furthermore, the deduced excitation energy means that any remaining transitions from the cascade that were not observed by Darby *et al.* [6,7] or by Sapple *et al.* [8] would be of low energy and would probably have a large internal conversion coefficient. The α-decay Q value is plotted in Fig. 4, from which it can be seen that ^{160}Re exhibits a larger increase in Q value than might be expected from the Q values of its heavier isotopes. A similar increase in Q value is also found for its Ta, W, and Os isotones that are plotted and for the ground states of Ta and Re isotopes at $N = 85$.

The measured half-life and α-decay branching ratio for ^{164}Ir give a partial α-decay half-life of 1.8 ± 0.9 ms. Using the method of Rasmussen [41] yields a reduced α-decay width of 33 ± 17 keV, which is consistent with an unhindered $\Delta l = 0$ decay and is comparable to the value of 43 ± 3 keV determined for ^{166}Ir [4].

The partial half-lives for proton emission from ^{164,165}Ir deduced from the measurements in the present work are 73 ± 10 μs and 370 ± 40 μs, respectively. Comparison with Wentzel–Kramers–Brillouin (WKB) calculations using the global optical model of Becchetti and Greenlees [42] assuming proton emission from a $\pi h_{11/2}$ orbital yields reduced proton-decay widths of 0.29 ± 0.04 and 0.30 ± 0.05, respectively. As can be seen in Fig. 5(a), both of these values are consistent with the value of 1/3 that would be expected from the low-seniority shell-model calculation proposed by Davids *et al.* [4] but are lower than spectroscopic factors calculated in the BCS theory using the proton pairing strength from Ref. [43] and proton single-particle energies from Ref. [44]. Figure 5(b) shows the proton-decay half-lives calculated for the $\pi h_{11/2}$ states of Ta,

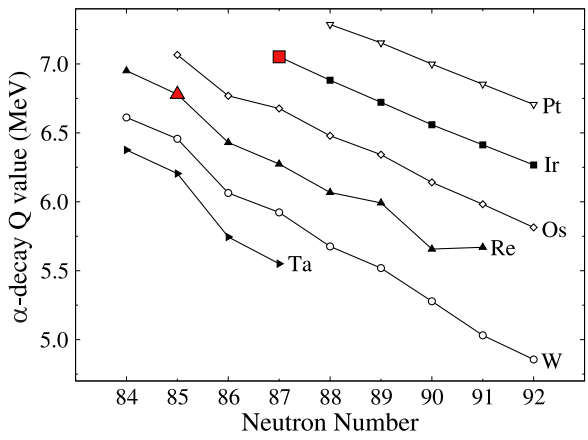


FIG. 4. (Color online) Q values of α decays of $\pi h_{11/2}$ states in odd-Z nuclei and the ground states of even-Z nuclei. The measured value for ^{164}Ir obtained in the present work and the Q value for ^{160}Re deduced from it are indicated by the larger red symbols. Data are taken from Refs. [3,4,16–19,25–40]. The value plotted for ^{164}Re$_{89}$ corresponds to the α-particle energy of 5486 keV discussed in Ref. [39].

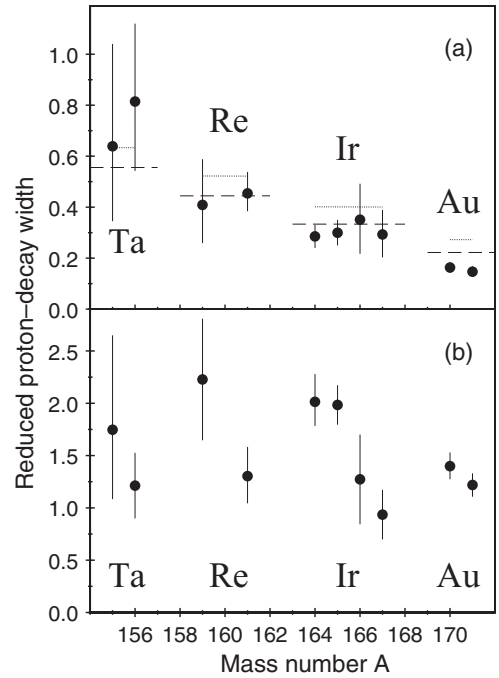


FIG. 5. Reduced proton-decay widths of $\pi h_{11/2}$ states of Ta, Re, Ir, and Au nuclei. (a) Values calculated using the WKB approximation compared with spectroscopic factors from low-seniority shell-model calculations (dashed lines) and BCS theory (dotted lines). (b) Values calculated using the simple formula from Ref. [45]. Experimental data are taken from Refs. [2–5,16,19,23,38,46], and the present work.

Re, Ir, and Au nuclei using the simple formula in Ref. [45] divided by the corresponding measured partial half-life. The experimental values for ^{164,165}Ir are approximately a factor of two shorter than predicted, but there does seem to be a tendency for the formula to predict longer half-lives than are measured for the states that are plotted.

V. SUMMARY

The decay properties of the lightest-known iridium isotope ^{164}Ir have been investigated, resulting in improved measurements for its proton-decay branch. The α-decay branch of the $\pi h_{11/2}$ isomeric state in ^{164}Ir has been identified, establishing the excitation energy of the corresponding state in the daughter nuclide, ^{160}Re. The results agree well with values estimated from local extrapolations of the systematics of proton-decay Q values [9]. Corresponding estimates for the even-lighter isotopes ^{162,163}Ir suggest that half-lives of 90 ns and 410 ns, respectively, could be expected [9], which may be too short for study using recoil separator devices such as that used in the present work. Extrapolating the nearly linear variation of α-decay Q values with neutron number for Ir isotopes suggests that a partial half-life of $\sim$300 μs could be expected for the $\pi h_{11/2}$ state in ^{163}Ir. This would imply an α-decay branching ratio of only $\sim$0.1%. A similar branching ratio could be expected for ^{162}Ir, assuming that its Q value has an increase similar to that seen in its $N = 85$ isotones. With such low branching ratios, short half-lives, and expected low production cross sections, ^{164}Ir could be the lightest Ir isotope in which an α-decay branch can be identified.

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