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α decay of ^{159}Re and proton emission from ^{155}Ta

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The α decay of ^{159}Re has been observed for the first time in reactions of 300 MeV ^{58}Ni ions with an isotopically enriched ^{106}Cd target. The ^{159}Re ions were separated in-flight using the RITU separator and implanted into the GREAT spectrometer. The α decay emanates from the proton-emitting $\pi h_{11/2}$ state in ^{159}Re with an energy of $E_\alpha = 6776 \pm 26$ keV and a branching ratio of $7.5 \pm 3.5\%$. This α decay populates a state in the closed neutron shell nucleus ^{155}Ta, which decays by emitting 1444 ± 15 keV protons with a half-life of $2.9^{+1.5}_{-1.1}$ ms. These values are consistent with the emission of the proton from a $\pi h_{11/2}$ orbital. These results fit in with the systematics of proton and α-particle separation energies in the region, but disagree with the previously reported decay properties of ^{155}Ta.

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The quest to understand the complex interactions between the constituent nucleons of atomic nuclei has motivated investigations into nuclei under extreme conditions of temperature, angular momentum, and isospin. The push to extreme values of isospin has resulted in the discovery of many new nuclides beyond the proton drip line, where decay spectroscopy has proved to be a highly effective tool for extracting detailed information about the structure of proton-emitting nuclei [1,2].

For proton emitters below the $N = 82$ neutron shell closure, where β decay is the main competing decay process, the identification has relied on their relatively short half-lives which allows temporal and spatial correlations with the parent nuclei implanted into double-sided silicon strip detectors (DSSDs) deployed at the focal plane of a recoil separator. The fine segmentation of the DSSDs suppresses the background from the β particles [3], while the ratio of the mass of the implanted ion to its ionic charge state combined with the systematic behavior of proton separation energies can allow an unambiguous assignment of the proton decay to a specific nuclide. Using this approach, important information about the deformation and single particle structure of these extremely neutron-deficient nuclides has been deduced [4,5].

Proton-emitting nuclei have also been extensively studied in the region above $N = 84$, where α decay can occur as a significant competing decay mechanism. Although α emission reduces the yield of proton peaks when the decays emanate from the same state and can also give rise to significant background at energies where proton lines occur, α decays do provide the opportunity for correlating proton emitters' decay chains. Consequently, even very weakly produced decay lines can be identified and their decay properties established with confidence. This reliable and sensitive method of correlating with α decays has allowed a large number of cases of proton emission to be studied, resulting in extensive systematics of relative energies of single-particle orbitals and proton spectroscopic factors of nuclei in this region [6,7].

Nuclei in the intermediate zone just below $N = 84$ represent particularly difficult cases for proton decay studies because correlations with subsequent α decays are delayed by the β decays of intermediate nuclides. Furthermore, less neutron-deficient isobars can undergo α decay with short half-lives. This leads to a situation where it is difficult to isolate the proton decays from the background arising from escaping α particles through correlations with the implanted ions. In addition, correlations with the α-decaying descendants are so slow that significant background from random correlations can render the peaks unobservable.

A prime example of just such a difficult case is the proton decay of the $N = 82$ nuclide ^{155}Ta studied using the Fragment Mass Analyzer at the Argonne National Laboratory [8]. The background in that case arose from the 7.39 MeV α decays of an isomeric state in ^{155}Lu that has a half-life of only 2.71 ms [9] and was produced very strongly as an evaporation residue. To suppress this background, a spectrum was obtained by selecting only decay events that occurred within 30 μs of an ion implant in the same DSSD pixel and were followed by an α decay of the great granddaughter ^{154}Yb (see inset to Fig. 1(c)). This second correlation stage is extremely difficult because the *average* time interval between any proton decay and the subsequent ^{154}Yb α decay is over 5 s [9–11]. The peak in this final spectrum was assigned as the proton decay of ^{155}Ta and comprised six counts at an energy of 1765 ± 10 keV.

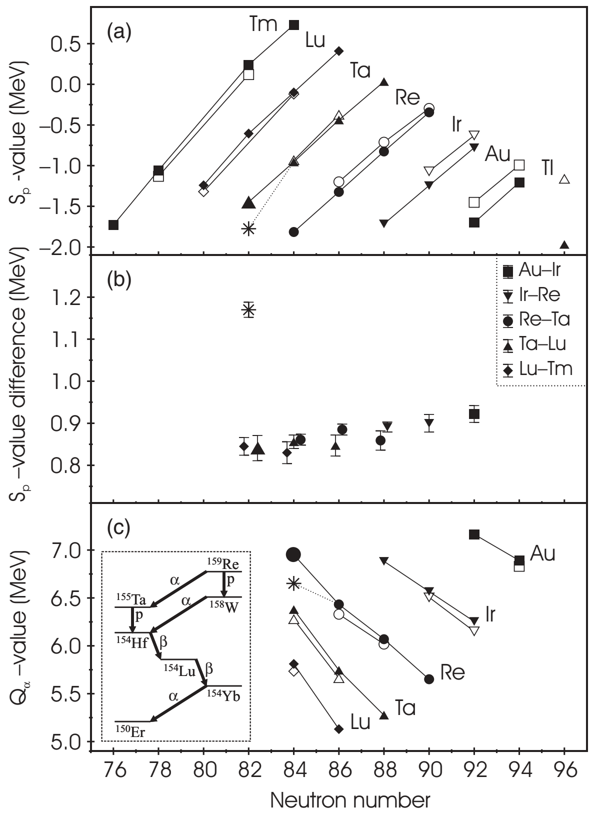

FIG. 1. (a) Measured S_p-values of odd-Z, even-N nuclides of elements between Tm and Tl. The asterisk represents the ^{155}Ta value from [8] and the large filled triangle is taken from the present work. (b) Differences in the S_p-values for $\pi h_{11/2}$ states of isotones of consecutive odd-Z elements. The value of $S_p(^{153}\text{Lu})-S_p(^{155}\text{Ta})$ calculated using the value for ^{155}Ta from Ref. [8] is plotted with the asterisk symbol while the value deduced from the present work is represented by the large filled triangle. In cases where more than one data point can be determined for a given isotone, the points are displaced slightly from the true neutron number for clarity of presentation. (c) Measured α-decay Q-values of odd-Z, even-N nuclides. The asterisk represents the value deduced from Q_α-value for ^{158}W [12] and the S_p-values for ^{155}Ta [8] and ^{159}Re [6]. The Q-value measured for ^{159}Re in the present work is denoted by the large filled circle. Other data are taken from Refs. [2,7,9,13–20]. The inset shows the decay paths originating from the $\pi h_{11/2}$ state in ^{159}Re. In (a) and (c) filled symbols correspond to the $\pi h_{11/2}$ states, while open symbols represent the $\pi s_{1/2}$ states and the error bars are smaller than the size of the plotted symbols. Solid lines connect values for the same odd-proton configuration in a given isotopic chain.

Even with such stringent correlation conditions for the first decay, significant levels of background are still evident in the spectra [8].

Although the reported decay energy and half-life for ^{155}Ta are compatible with emission from a $\pi h_{11/2}$ orbital, the reported proton separation energy of -1776 ± 10 keV for ^{155}Ta [8] clearly deviates markedly from the monotonic variation of the S_p-values as a function of neutron number shown in Fig. 1(a). The anomaly cannot be attributed to the $N = 82$ shell closure, because no corresponding effect is seen for the Tm or Lu isotopic chains. This deviation is even more striking in Fig. 1(b), where the differences in S_p-values of the isotones of adjacent odd-Z nuclides [e.g., $S_p(^{153}\text{Lu})$–$S_p(^{155}\text{Ta})$] are plotted. From these plots, it appears that there is a discrepancy of ~300 keV in the S_p-value for ^{155}Ta.

The recent discovery of proton emission from a $\pi h_{11/2}$ orbital by ^{159}Re [6] also raises questions about those previously reported results for ^{155}Ta [8]. In particular, it is possible to deduce the α-decay Q-value for ^{159}Re, assuming the α decay feeds the reported proton-emitting state in ^{155}Ta, since $Q_\alpha(^{159}\text{Re}) = Q_\alpha(^{158}\text{W}) - S_p(^{159}\text{Re}) + S_p(^{155}\text{Ta}) = 6652 \pm 23$ keV [6,8,12]. This value appears to be anomalously low compared with the systematics of Q_α-values plotted in Fig. 1(c) and is in fact even smaller than the value of 6711 ± 16 keV measured for the neighboring isotope nearer stability, ^{160}Re [9]. Such a low value is hard to explain and casts further doubt on the assignment of the peak observed in Ref. [8] to the proton decay of the lowest-lying $\pi h_{11/2}$ state in ^{155}Ta.

In this Rapid Communication, the first observation of the α decay of ^{159}Re is presented, along with the proton decay properties of the state in ^{155}Ta that this populates. These new measurements benefit from the fast direct correlations between these short-lived decays and are compared with the systematic behavior of nuclei in this region. Possibilities for the origin of the peak previously assigned as the proton decay of ^{155}Ta are explored.

The experiment was performed at the Accelerator Laboratory of the University of Jyväskylä and has previously been outlined in Ref. [6], so only a very brief description will be given here. The ^{159}Re nuclei were populated in the $^{106}\text{Cd}(^{58}\text{Ni},p4n)$ complete fusion evaporation reaction. A beam of 300 MeV ^{58}Ni ions bombarded a 1.1 mg/cm^2 thick, self-supporting ^{106}Cd target foil of 96.5% isotopic enrichment. The average beam current of 4.7 pnA was delivered over a period of 75 h. Fusion reaction products were separated in-flight using the RITU gas-filled separator [21] and implanted into one of the two DSSDs of the GREAT spectrometer [22].

Each of the adjacently mounted DSSDs had an active area of 60 mm × 40 mm and a nominal thickness of 300 μm. The strips on the front surface of the DSSD were orthogonal to those on the back surface and the strip pitch of 1 mm on both faces gave a total of 4800 independent pixels. A multiwire proportional counter provided energy loss and (in conjunction with the DSSDs) time-of-flight information to distinguish between recoiling nuclei and any residual scattered beam. It also provided discrimination between recoil implants and decay events via a simple (anti)coincidence with the DSSDs. The average recoil implantation rate was ~2 kHz.

All detector signals were passed to the triggerless total data readout data acquisition system [23] where they were time stamped with a precision of 10 ns to facilitate temporal correlations between recoil implants and their subsequent radioactive decays.

In the recent report of the discovery of ^{159}Re by Joss *et al.* [6], no evidence could be found for α decays of ^{159}Re correlated with proton decays of ^{155}Ta having the previously published properties [8]. However, given the questions surrounding those ^{155}Ta data, the present data were searched for any evidence of an α-decay branch from ^{159}Re followed by proton decays of ^{155}Ta with much less restricted proton energy

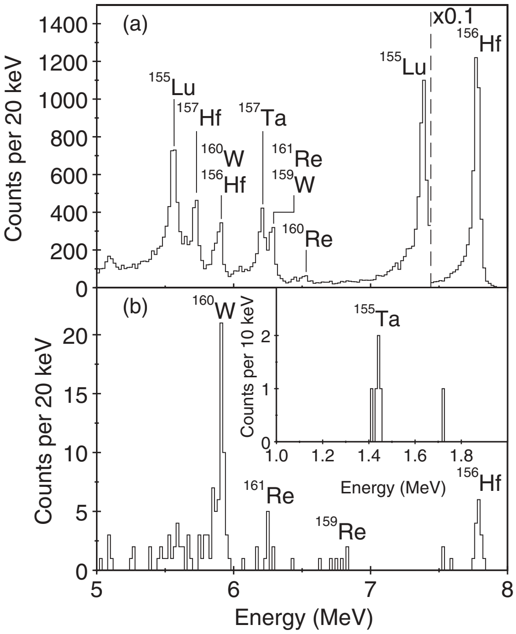

FIG. 2. (a) Energy spectrum of all decays occurring within 100 μs of the implantation of an evaporation residue in the same DSSD pixel. Known α-decay lines are labeled. (b) Decays in (a) that were followed within 10 ms by a signal in the energy range 1.1–1.8 MeV, corresponding to possible proton decays of ^{155}Ta. The counts at ~6.8 MeV represent a new activity that is assigned as the α-decay branch from the $\pi h_{11/2}$ state in ^{159}Re. The inset shows the energy spectrum of decays occurring within 10 ms of events in the ^{159}Re α-decay peak. The peak at ~1.4 MeV is assigned as the proton decay of the lowest-lying $\pi h_{11/2}$ state in ^{155}Ta.

and correlation time constraints. The measured half-life of the $\pi h_{11/2}$ state in ^{159}Re is 21 ± 4 μs, so any α-decay branch from this state should be observed with the same half-life. Figure 2(a) shows the energy spectrum of all decays occurring within 100 μs of the implantation of an evaporation residue into the same GREAT DSSD pixel. This spectrum is dominated by the 7.8 MeV α decay of the 0.5 ms 8^+ isomer in ^{156}Hf [9].

Figure 2(b) shows the decays from Fig. 2(a) that were then followed within 10 ms by a signal in the energy range 1.1–1.8 MeV, which would correspond to possible proton decays of ^{155}Ta. Known α-decay lines below 6.5 MeV appear because the broad energy gate for the proton decays encompasses part of the energy spectrum of α particles that deposit only part of their energy as they escape from the DSSD in the backward direction (see Fig. 2 of Ref. [6]). These α-decay lines then appear through correlations with their escaping daughter α decays. The ^{156}Hf peak can be understood as arising when a ^{156}Hf ion is implanted and decays shortly before an uncorrelated escaping α decay of a longer-lived nuclide occurs in the same DSSD pixel. The occurrence of this small number of random correlations reflects the large number of counts in the ^{156}Hf peak in Fig. 2(a). Reducing this proton decay time gate from 10 ms to 100 μs results in an empty spectrum, confirming that there is no evidence in these data for α decays of ^{159}Re correlated with the 1776 keV, 12 μs proton activity reported in Ref. [8].

The counts at 6776 ± 26 keV represent a new activity, the half-life of which was measured to be 16 ± 9 μs using the method of maximum likelihood [24]. This half-life is an order of magnitude too short to result from a nucleus produced in this fusion reaction decaying by α emission alone, but is consistent with the value measured for the proton decay of ^{159}Re [6]. It is therefore assigned as the α-decay branch of the $\pi h_{11/2}$ state in ^{159}Re. The α-decay branching ratio measured for this state was 7.5 ± 3.5%.

The inset to Fig. 2(b) shows the energy spectrum of events that followed the ^{159}Re α decays within 10 ms. The peak at 1444 ± 15 keV is assigned as the proton decay of ^{155}Ta. Combining the α-decay Q-value for ^{159}Re with that for this proton decay of ^{155}Ta yields a total of 8405 ± 30 keV. This compares with the total of 8428 ± 20 keV obtained by summing the Q-values for ^{159}Re proton-decay [6] and ^{158}W α decay [12]. These values are mutually consistent, which supports the interpretation that the new correlated activities start from the $\pi h_{11/2}$ state in ^{159}Re and end at the ground state of ^{154}Hf (see inset to Fig. 1(c)). The half-life of this new proton decay line was measured to be $2.9^{+1.5}_{-1.1}$ ms using the method of maximum likelihood [24]. The single count at 1725 keV occurs over 2 ms after the first decay, so it is incompatible with the 12 μs activity assigned as ^{155}Ta in the previous study. Furthermore it is inconsistent with the sum of the Q values and is therefore presumed to be background.

The Q-value for the α-decay of ^{159}Re measured in the present work is included in the data presented in Fig. 1(c). It fits in well with the systematics, showing the slightly larger increase in Q-value that is observed at $N = 84$ for the isotones ^{155}Lu and ^{157}Ta. From the decay energy and branching ratio measured in the present work and the half-life deduced from the ^{159}Re proton decays [6], a reduced width of $\delta^2 = 81 \pm 44$ keV is deduced using the method of Rasmussen [25]. This agrees well with values measured for decays of nuclei in this region, although the uncertainty is large owing to the small number of counts.

The measurement of an α-decay branch from ^{159}Re allows the partial half-life for proton emission from this state to be determined. Correcting for the branching ratio gives a partial proton decay half-life of 23 ± 6 μs and the revised spectroscopic factor after allowing for the α-decay branch is 0.41 ± 0.15. This compares with the expected value of 0.44 for a Re proton emitter [7] and does not alter substantially the conclusions drawn in ref. [6] about the proton being emitted from a $\pi h_{11/2}$ orbital.

The half-life measured for the ^{155}Ta proton decay in the present work is much shorter than the value of ~330 ms predicted for its β decay [26], so this β-decay branch is expected to have a negligible effect on the partial half-life for proton decay. The measured half-life can be compared with values calculated for the different possible proton orbitals and the measured ^{155}Ta proton decay energy. Using the WKB approximation with the potential of Becchetti and Greenlees [27] yields calculated values of 91 ns, 0.78 μs and 1.8 ms for the $s_{1/2}$, $d_{3/2}$, and $h_{11/2}$ proton orbitals, respectively. The measured value is only compatible with that calculated for the $\pi h_{11/2}$ orbital. Furthermore, the present measurements for both ^{155}Ta and ^{159}Re agree well with the systematics of proton emission for nuclei with Z > 68, provided the protons are emitted from $h_{11/2}$ orbitals [28]. From the ratio of the calculated and the measured half-life a spectroscopic factor of $0.63^{+0.38}_{-0.31}$ can be deduced. This compares with the value of 0.55 expected from a low-seniority shell model calculation for a tantalum isotope [7]. Similar conclusions are reached from calculations performed using either the WKB approximation or a two potential method [29] with a potential generated by the Hartree-Fock approach with the SkP Skyrme force [30].

The proton separation energy deduced for ^{155}Ta in the present work is included in the data plotted in Fig. 1(a). The new value fits in very well with the systematic trends, continuing the expected monotonic decrease in S_p-values with decreasing neutron number. This agreement is also evident in Fig. 1(b), where the new result is seen to follow the smoothly varying behavior established for other nuclides in this vicinity. This is a strong indication that the proton peak observed in the present work represents the decay of the lowest-lying $\pi h_{11/2}$ state in ^{155}Ta.

The origin of the previously published results for ^{155}Ta [8] is an interesting question. Joss *et al.* suggested the possibility that it could represent the decay of an isomeric state in ^{155}Ta [6]. In the lighter $N = 82$ isotones, seniority 3 $(\pi h_{11/2})^3 27/2^-$ isomers have been identified in the odd-Z nuclides ^{149}Ho, ^{151}Tm, and ^{153}Lu [31–33]. The corresponding isomer in ^{155}Ta could be populated directly in the fusion reaction employed in Ref. [8], but would not have been fed by the α decay of ^{159}Re in the present work. The proton decay of the isomer could decay directly to the seniority 2 $(\pi h_{11/2})^2 10^+$ isomer in ^{154}Hf [32,33] in order to avoid the hindrance due to configuration changes by decaying directly to the ^{154}Hf ground state. However, a more likely decay path is to the 8^+ state in ^{154}Hf, since this would be favored by a higher Q-value than the decay to the 10^+ state.

Figure 3(a) shows the excitation energies of the $27/2^-$ isomers and 8^+ states observed in $N = 82$ isotones plotted as a function of atomic number. The excitation energies appear to follow a parabolic trend for both the odd-Z and the even-Z isotones and a parabolic fit allows the excitation energy of the $27/2^-$ state in ^{155}Ta to be estimated. The $27/2^-$ states in $^{149}_{67}$Ho, $^{151}_{69}$Tm, and $^{153}_{71}$Lu lie lower in energy than the 8^+ states in $^{148}_{66}$Dy, $^{150}_{68}$Er, and $^{152}_{70}$Yb, which would be the respective daughters of their proton decays. Consequently, the proton decay Q-values of these isomeric states to the 8^+ states are *lower* than those of the $11/2^-$ states to the ground states. Figure 3(b) shows this reduction in the proton decay Q-value plotted as a function of atomic number of the putative proton emitter. In the case of ^{155}Ta, the estimated Q-value is comparable with that of the lowest-lying $\pi h_{11/2}$ state and would clearly be incompatible with a value ~300 keV larger. Furthermore, the known isomers all have very short half-lives (~35μs, or less), so it would be surprising if an isomer with such an increased excitation energy were not to decay predominantly by γ-ray emission.

Shell model calculations have been performed by Lawson [34] for the $N = 82$ isotones, assuming that excited states are formed by the coupling of the valence $h_{11/2}$ protons. Although these calculations achieve remarkable agreement with the measured properties of these isomeric states, they give no indication that other isomers with sufficiently long lifetimes should be expected. Since the proton emission previously reported for ^{155}Ta is purportedly from a $\pi h_{11/2}$ orbital, it is therefore difficult to see how emission from an isomeric state can provide the explanation of those results.

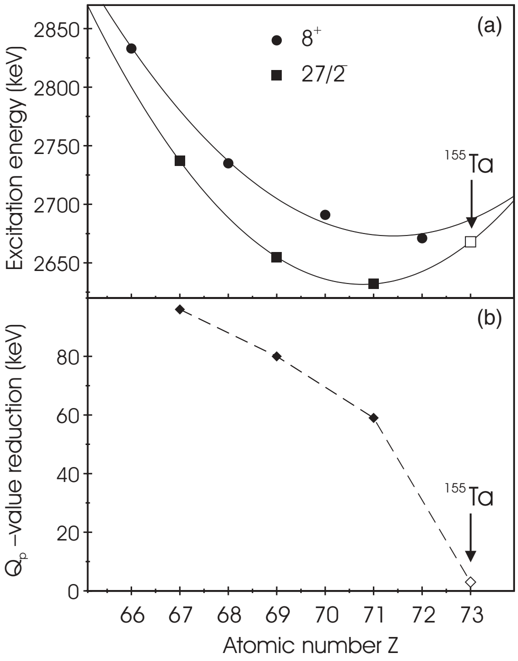

FIG. 3. (a) Excitation energies of $27/2^-$ isomers and 8^+ states observed in $N = 82$ isotones plotted as a function of atomic number. Parabolic fits to the measured excitation energies are shown by the solid lines. Data are taken from Refs. [31–33]. (b) Reduction in Q-values for proton emission from the $27/2^-$ isomers to the 8^+ states, relative to those for the lowest-lying $\pi h_{11/2}$ states to the ground states, plotted against the atomic number of the potential proton emitter. Expected values for ^{155}Ta are indicated.

In summary, new experimental results for the proton decay of ^{155}Ta have been obtained in the present work. The ^{155}Ta nuclei were populated through the newly discovered α decay of ^{159}Re and these short-lived radioactivities have allowed clean correlations to be obtained. The measured decay properties are compatible with the decays of $\pi h_{11/2}$ states in both nuclides and provide excellent agreement with the systematic behavior of nuclei in this region. However, they disagree with the previously reported decay properties of ^{155}Ta. Verifying or discounting those experimental results by improving on the background conditions would be a challenging but very important measurement. While the difficulties of such experiments are amply illustrated by the case of ^{155}Ta, it does appear that the smooth evolution of nuclear properties can still provide valuable guidance for future investigations into nuclear properties at this proton-rich extreme of isospin.

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