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Decay of the high-spin isomer in ^{160}Re: Changing single-particle structure beyond the proton drip line

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ABSTRACT

A new high-spin isomeric state ($t_{1/2} = 2.8 \pm 0.1$ μs) in ^{160}Re has been identified. This high-spin isomer is unique in that it only decays by γ-decay and not by proton or α-particle emission as is the case in every other proton emitter between $Z = 64$ and 80. Shell model calculations indicate how the convergence of the $h_{9/2}$ and $f_{7/2}$ neutron levels in this region could open up a γ-decay path from the high-spin isomer to the low-spin ground state of ^{160}Re, providing a natural explanation for this anomalous absence of charged-particle emission. The consequences of these observations for future searches for proton emission from even more exotic nuclei and in-beam spectroscopic studies are considered.

Understanding nuclei far from β stability is one of the key challenges in nuclear physics and impressive advances in addressing this issue are being achieved. At the limits of proton-rich nuclei, over 30 proton emitters have been discovered, with nearly half of this rich sample coming from the region of the proton drip line bounded by the $N = 82$ and $Z = 82$ shell closures. This success has been made possible by exploiting recoil separators capable of isolating these ephemeral species on a microsecond timescale and implanting them into a position sensitive silicon detector system. The remarkable selectivity that can be obtained through correlations with the characteristic decays of their daughter nuclides has allowed a systematic understanding of some of the features of these nuclei to emerge [1–13].

The structure of nuclei in this region is dominated at low excitation energy by valence neutrons in the $\nu f_{7/2}$ and $\nu h_{9/2}$ orbitals and protons in the $\pi s_{1/2}$, $\pi d_{3/2}$ and $\pi h_{11/2}$ orbitals [14,15]. In odd-Z nuclei, two states are generally seen at low excitation energy that can decay by proton, α or β emission: in odd-A nuclei the states usually have either an unpaired $s_{1/2}$ or $h_{11/2}$ proton, while in odd–odd nuclei either a $d_{3/2}$ or $h_{11/2}$ proton is coupled with an $f_{7/2}$ neutron to form the low-lying states. According to the Nordheim rules [16,17], the lowest-energy state formed by coupling a $d_{3/2}$ proton with an $f_{7/2}$ neutron would have spin and parity 2^-, while the lowest-energy state would be 9^+ when coupling an $h_{11/2}$ proton with an $f_{7/2}$ neutron. Thus, in both odd-A and odd–odd nuclei γ-decays between the $\pi h_{11/2}$ and the $\pi s_{1/2}$ or the $\pi d_{3/2}$ states would be very slow owing to the large spin difference, so charged particle emission dominates.

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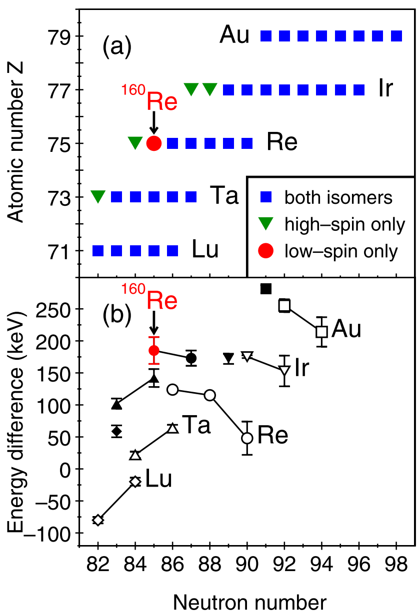

Fig. 1. (a) Chart indicating the observed low-lying isomers in odd-Z nuclei. The triangles indicate nuclei in which only the high-spin isomer has been observed, the squares indicate those in which both the high-spin and low-spin isomers have been observed and the circle indicates ^{160}Re, which is the only nuclide in this region where only the low-spin isomer has been observed. (b) Excitation energy of $\pi h_{11/2}$ isomers above low-spin ($\pi s_{1/2}$ or $\pi d_{3/2}$) isomers. The open symbols denote odd-A nuclei, while odd–odd nuclei are indicated by the filled symbols. The value plotted for ^{160}Re$_{85}$ is estimated from proton-decay Q-value systematics. Data are taken from Refs. [2–8].

This pattern of two low-lying states is generally borne out, see Fig. 1(a), except for a few of the most exotic nuclei where only the $\pi h_{11/2}$ state has been observed, presumably because the low-spin state is too short-lived to survive the flight time through a recoil separator [6–10]. The only other exception to this rule is the first proton emitter discovered in the region above $N = 82$, the odd–odd nuclide ^{160}Re [1]. Contrary to the general picture that has since emerged from subsequent studies of nuclei in this vicinity, only proton and α-decays of the $\pi d_{3/2}$ state were observed in that work. No evidence has been reported for a state involving an unpaired $h_{11/2}$ proton in ^{160}Re, even though this would be expected to be produced more strongly than the $\pi d_{3/2}$ state in fusion-evaporation reactions, owing to its higher spin. This non-observation appears even more surprising when one considers that proton emission has been observed from the $\pi h_{11/2}$ state of its more exotic isotope ^{159}Re [9]. In this Letter we present a detailed investigation searching for the $\pi h_{11/2}$ state in ^{160}Re and consider the implications of our findings for future studies of nuclei at the limits of observable heavy proton-rich nuclei.

The present experiment was performed at the Accelerator Laboratory of the University of Jyväskylä. The ^{160}Re nuclei were produced by the reaction of ^{58}Ni ions impinging on a 1.1 mg/cm^2 thick, self-supporting ^{106}Cd target foil of 96.5% isotopic enrichment. An average beam current of 2 particle nA was delivered for 68 hours at 290 MeV, while an average current of 4.7 particle nA was delivered at 300 MeV for 75 hours. Fusion reaction products were separated in-flight by the RITU gas-filled separator [18], then implanted into the double-sided silicon strip detectors (DSSDs) of the GREAT spectrometer [19]. Each of the DSSDs had an active area of 60 mm × 40 mm, a thickness of 300 µm and a strip pitch of 1 mm on both faces, giving a total of 4800 independent pixels. A Multiwire Proportional Counter provided discrimination between evaporation residues, scattered beam and decay particles. A planar double-sided germanium strip detector was mounted a few mm behind the DSSDs inside the same vacuum enclosure to measure low-energy γ rays. It had an active area of 120 mm × 60 mm, a thickness of 15 mm and a strip pitch of 5 mm. The efficiency of the planar Ge detector had a maximum value of 16% at 120 keV. Below 20 keV the efficiency dropped rapidly owing to absorption in the DSSDs and the Ge detector's 0.5 mm thick Be window. All detector signals were passed to the GREAT triggerless total data readout data acquisition system [20] where they were time stamped with a precision of 10 ns to allow flexible offline data analysis.

Analysis of the present data has confirmed the previous observations of proton and α-particle emission from the $\pi d_{3/2}$ ground state of ^{160}Re [1]. This experiment was also sensitive to the γ-decay of isomers surviving the ≈ 0.4 µs flight time through RITU. Fig. 2(a) shows the energy spectrum of γ rays measured in the planar Ge detector within 24 µs of the implantation of ions correlated with either the proton or α-decay branch of ^{160}Re. There are distinct peaks at 38 keV and 96 keV, in addition to the Re K_α and K_β X ray peaks, and there is possibly another peak at around 50 keV. A half-life of 2.8 ± 0.1 µs was deduced from the combined data for the 38 keV and 96 keV peaks using the method of maximum likelihood [21]. The same peaks and isomer lifetimes were observed when gating separately on the proton and α-decay branches of ^{160}Re, providing further evidence that these decays emanate from the same initial state.

The 96 keV peak is the only observed γ ray transition having an energy above 72 keV, the Re K-shell binding energy, so the X rays come from the electron conversion of this transition. From the relative intensities of the 96 keV line and the K X rays, a K-shell conversion coefficient of 1.2 ± 0.4 was deduced after correcting for the Ge detector efficiency. This agrees well with the calculated K-shell conversion coefficient of 0.9 for an E2 transition [22]. The lifetime expected for a 96 keV E2 transition is ~ 0.2 µs [23], indicating that this is the transition by which the isomeric level directly decays, feeding other levels in the γ-decay cascade to the $\pi d_{3/2}$ ground state.

The segmentation of the planar germanium detector allowed a γ–γ coincidence analysis to be performed. Figs. 2(b) and 2(c) show the energy spectra of γ rays observed in the planar Ge detector in coincidence with the 38 keV and 96 keV transitions, respectively, demonstrating that they are in prompt coincidence. The lifetime restricts the possible multipolarity assignments for the 38 keV line to either M1 or E1. The conversion coefficient for a 38 keV M1 transition is far too large to be compatible with the 96 keV γ ray intensity, whereas an E1 assignment would give equal intensities within uncertainties after correcting for internal conversion. On this basis we confidently assign the 38 keV γ ray as an E1 transition.

The proportion of all ^{160}Re ions that were produced in the isomeric state can be deduced from the intensities of the 38 keV and 96 keV peaks, after correcting for internal conversion, the γ ray detection efficiency and in-flight decay losses through RITU. The isomeric ratio obtained is close to 100%, which is remarkable for an isomer that feeds a $\pi d_{3/2}$ state because the $\pi h_{11/2}$ configuration is much more strongly populated in fusion evaporation reactions owing to its higher spin. This suggests that the isomer is fed by high-spin structures, which in this region have $\pi h_{11/2}$ character.

The proton and α-decay properties expected for the $\pi h_{11/2}$ state in ^{160}Re are governed by the decay energies. Fig. 1(b) shows the excitation energies of the high-spin isomers above the low-spin isomers that have been deduced from proton-decay measurements, either directly or in combination with α-decay measurements. The excitation energies for odd–odd nuclei fall in the range $\sim$ 50–300 keV, so a similar value could be expected for