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Precision measurements of proton emission from the ground states of ^{156}Ta and ^{160}Re

I. G. Darby,* R. D. Page, D. T. Joss, L. Bianco,† T. Grahn,* and D. S. Judson
Department of Physics, University of Liverpool, Liverpool L69 7ZE, United Kingdom

J. Simpson
STFC, Daresbury Laboratory, Daresbury, Warrington WA4 4AD, United Kingdom

S. Eeckhaudt, P. T. Greenlees, P. M. Jones, R. Julin, S. Juutinen, S. Ketelhut, M. Leino, A.-P. Leppänen,‡ M. Nyman, P. Rahkila, J. Sarén, C. Scholey, A. N. Steer,§ J. Uusitalo, and M. Venhart‖
Department of Physics, University of Jyväskylä, P.O. Box 35, FIN-40014 Jyväskylä, Finland

S. Ertürk
Nigde Universitesi, Fen-Edebiyat Falkültesi, Fizik Bölümü, Nigde, Turkey

B. Gall
IPHC, CNRS-IN2P3, ULP Strasbourg, 23 rue de Loess, F-67037 Strasbourg cedex 2, France

B. Hadinia†
Royal Institute of Technology, Alba Nova Center, S-106 91 Stockholm, Sweden
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The decays of the $\pi d_{3/2}$ ground states of ^{156}Ta and ^{160}Re have been studied in detail using the GREAT spectrometer. More than 7000 ^{160}Re nuclei were produced in reactions of 290- and 300-MeV ^{58}Ni ions with an isotopically enriched ^{106}Cd target and separated in flight using the RITU separator. The proton and α decays of the $\pi d_{3/2}$ level were confirmed and the half-life and branching ratios of this state were determined with improved precision to be $t_{1/2} = 611 \pm 7$ μs and $b_{\mathrm{p}} = 89 \pm 1\%$ and $b_\alpha = 11 \pm 1\%$, respectively. The α-decay branch populated the ground state of ^{156}Ta, allowing improved values for the proton-decay energy and half-life to be obtained ($E_p = 1011 \pm 5$ keV; $t_{1/2} = 106 \pm 4$ ms). The β decay of this level was identified for the first time and a branching ratio of $b_\beta = 29 \pm 3\%$ was deduced. The spectroscopic factors deduced from these measurements are compared with predictions.

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I. INTRODUCTION

Proton emitters in the vicinity of the $N = 82$ shell closure are expected to be nearly spherical and have a core that displays vibrational properties [1,2]. The measured decay energies and partial half-lives of proton emitters in this region agree well with calculations using a simple one-dimensional model with a global optical model potential and the WKB approximation. Comparison of the measured and calculated half-lives allows spectroscopic factors to be deduced. For proton emission from $\pi s_{1/2}$ and $\pi h_{11/2}$ states, the spectroscopic factors are consistent with values predicted using a low-seniority shell model calculation [3]. However, the spectroscopic factors observed for proton emission from $\pi d_{3/2}$ orbitals in odd-odd nuclei are consistently lower than those predicted using this spherical shell model approach or BCS calculations [4]. This led to the development of more sophisticated models which take into account the role of dynamical particle-vibration coupling [1,2]. Although these calculations provided improved agreement with the experimental results, the data were not sufficiently precise to determine whether other effects need to be included. In the present work, precise measurements have been obtained for proton emission from the $\pi d_{3/2}$ ground states of ^{156}Ta and ^{160}Re, including a first measurement of the branching ratios for ^{156}Ta.

II. EXPERIMENTAL DETAILS

The 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

*Present address: Department of Physics, University of Jyväskylä, P.O. Box 35,FIN-40014, Jyväskylä, Finland.

†Present address: Department of Physics, University of Guelph, Guelph,Ontario, Canada N1G 2W1.

‡Present address: Northern Finland Regional Laboratory,STUK-Radiation and Nuclear Safety Authority, Rovaniemi, Finland.

§Present address: Department of Physics,University of York, Heslington Y01 5DD, United Kingdom.

‖Present address: Department of Nuclear Physics and Biophysics, Comenius University,Mlynska Dolina, SK-842 48 Bratislava 4, Slovakia.

was delivered for 68 h at 290 MeV, while an average current of 4.7 particle nA was delivered at 300 MeV for 75 h. Fusion reaction products were separated in flight by the RITU gas-filled separator [5], then implanted into the double-sided silicon strip detectors (DSSDs) of the GREAT spectrometer [6]. Each of the DSSDs had an active area of 60×40 mm, a thickness of 300 μm, and a strip pitch of 1 mm on both faces, giving a total of 4800 independent pixels. The DSSD energy calibration was based on the ^{160}Re proton decay [7] line and the implanted α-decay lines of Tb, Dy, Lu, and Hf nuclei [8]. 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 the energies of low-energy γ rays. All detector signals were passed to the GREAT triggerless total data readout data acquisition system [9], where they were time stamped with a precision of 10 ns to allow flexible offline data analysis.

III. RESULTS

Analysis of the present data has confirmed and extended the results of the previous work [7]. As illustrated in Fig. 1, the observed state in ^{160}Re primarily decays via proton emission to the ground state of the α-particle emitter ^{159}W. Figure 2(a) shows the energy spectrum of protons that occurred within 3 ms of the implantation of an evaporation residue into the same DSSD pixel, which were also followed within 22 ms by an α decay of ^{159}W. The clear peak at 1264(6) keV corresponds to the previously reported ^{160}Re proton decay line [7,8] and contains over 6000 counts. With this 200-fold increase in the level of statistics it was possible to obtain a more precise

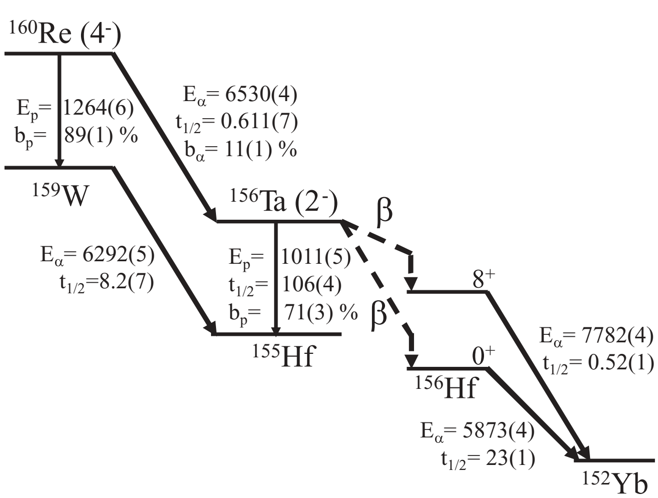

FIG. 1. Decay scheme of the $\pi d_{3/2}$ state in ^{160}Re. Decay energies in keV, half-lives in ms, and branching ratios are taken from the present work and Ref. [8]. The tentative spin and parity assignments for ^{160}Re and ^{156}Ta are given in parentheses. The dashed lines indicate unknown β decays that were searched for in this work. Of these, only the β decay of the $\pi d_{3/2}$ state in ^{156}Ta feeding the ground state of ^{156}Hf could be identified. Note that the β decays of ^{156}Ta may feed the α-emitting isomers in ^{156}Hf via intermediate states.

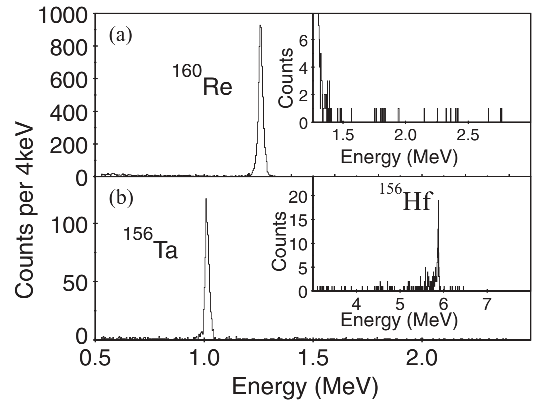

FIG. 2. (a) Energy spectrum of ^{160}Re proton decays following a recoil implantation within 3 ms and correlated within 22 ms with a subsequent α decay of ^{159}W in the same DSSD pixel. The inset shows the high-energy region of this spectrum with an expanded vertical scale. No peak is visible that could correspond to the proton decay of the $\pi h_{11/2}$ state in ^{160}Re. (b) Energy spectrum of decays of the $\pi d_{3/2}$ state in ^{156}Ta observed up to 320 ms after α decays of the $\pi d_{3/2}$ state in ^{160}Re that occur within 3 ms of the implantation of an ion into the same pixel. The inset shows the high-energy region of this spectrum, revealing the ground-state α-decay peak of ^{156}Hf, the β-decay daughter of ^{156}Ta.

half-life value of 614 ± 8 μs, which is consistent with the previously measured half-life of 790 ± 160 μs [7] and the assignment of $d_{3/2}$ character to the state.

An α-decay branch from ^{160}Re that feeds the $\pi d_{3/2}$ state in ^{156}Ta was also reported in the previous work [7] (see Fig. 1). Figure 3(a) shows the energy spectrum of α particles occurring within 3 ms of a recoil implantation in the same DSSD pixel that were then followed within 320 ms by a proton decay of the $\pi d_{3/2}$ state in ^{156}Ta. Several peaks are evident in this spectrum, but most arise because the proton peak lies in a region of the decay particle energy spectrum where there is background from α particles that escape from the DSSD. Background peaks can therefore appear for short-lived α emitters when the α particle from the daughter decay escapes and deposits only part of its energy in the DSSD, falling within the proton energy gate. These background peaks can be identified in Fig. 3(b), for which the energy gate has been set above the proton peaks but still includes a portion of the background from escaping α particles. Only one strong decay line in Fig. 3(a) does not also appear in Fig. 3(b) and this line is therefore attributed to the α decay of ^{160}Re.

The ^{160}Re α-decay peak contains approximately 650 counts. The energy of this line was found to be 6530 ± 4 keV and its half-life 597 ± 20 μs. Both of these values are compatible with those previously reported [7,8]. The previous measurements suggested that the proton and α decays from ^{160}Re originated from the same state and the half-lives measured with improved precision in the present experiment are still compatible with this interpretation. Combining the decay data for the proton and α-decay peaks, a half-life of 611 ± 7 μs was deduced for the $\pi d_{3/2}$ state in ^{160}Re.

A correlation analysis was also performed by gating on this ^{160}Re α-decay line using the same time conditions as

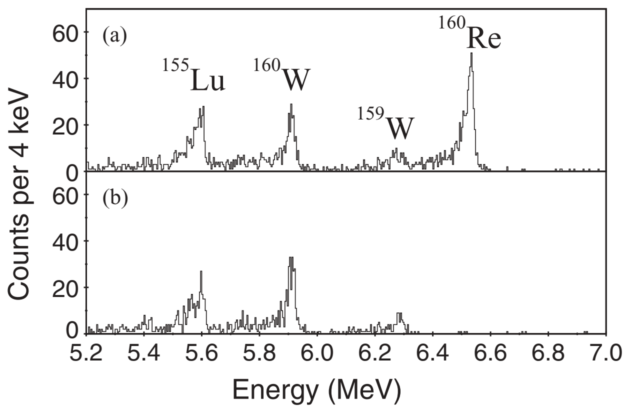

FIG. 3. (a) Energy spectrum of decays occurring within 3 ms of a recoil implantation and followed within 320 ms by the proton decay of the $\pi d_{3/2}$ state of ^{156}Ta. (b) As (a), except the energy region selected for the second decay is above the proton peak. This spectrum shows the background peaks that arise from correlations with escaping α particles when selecting proton decays.

above. The resultant spectrum shown in Fig. 2(b) shows clearly the peak arising from the proton decay of the $\pi d_{3/2}$ level in ^{156}Ta. From these data, the energy of this ^{156}Ta proton decay line was measured as 1011 ± 5 keV, while an improved value for its half-life of 106 ± 4 ms was obtained. The new energy measurements for the α decay of ^{160}Re and the proton decay of ^{156}Ta give a combined Q value of 7715 ± 6 keV. This compares with the sum of the Q values for the proton decay of ^{160}Re and the α decay of ^{159}W of 7726 ± 8 keV and is therefore consistent with both ^{160}Re decay branches proceeding from the same initial state in ^{160}Re to the ground state of ^{155}Hf.

The inset to Fig. 2(b) shows the high-energy portion of the same spectrum, in which an α-decay line attributed to the decay of the ground state of ^{156}Hf was observed. This line arises from the β-decay branch of the $\pi d_{3/2}$ state in ^{156}Ta (see Fig. 1), which is therefore identified for the first time in this work. No events were observed at around 8 MeV in this spectrum, indicating that the β decay of the $\pi d_{3/2}$ ground state in ^{156}Ta does not feed the α-decaying 8^+ state in ^{156}Hf with significant probability [8,10].

The relative intensities of the ^{156}Ta proton and ^{156}Hf α-decay peaks allow the branching ratios for the decays of the $\pi d_{3/2}$ state in ^{156}Ta to be deduced. Care needs to be taken to correct for the efficiency for detecting the full energy of both protons and α particles, which depends on the energy and particle type [8]. The resulting values are $b_p = 71 \pm 3\%$ and $b_\beta = 29 \pm 3\%$. The former value leads to a partial half-life of 149 ± 8 ms for the proton decay of this state, which is compatible with calculated values assuming proton emission from a $\pi d_{3/2}$ orbital [7]. The partial half-life for β decay is 366 ± 40 ms, which agrees well with the predicted value of 350 ms [11].

From the yields of the proton and α-decay peaks for ^{160}Re, it is possible to extract the branching ratios for each decay mode. The cleanest and therefore most reliable spectra are those obtained from correlation analyses, so the efficiency of the correlation energy and time gates has to be considered. Furthermore, the β decay of the $\pi d_{3/2}$ state in ^{156}Ta has to be taken into account. Following these corrections, the branching ratios for the proton and α-decay of the $\pi d_{3/2}$ state in ^{160}Re were measured to be $89 \pm 1\%$ and $11 \pm 1\%$, respectively. The partial half-life for the β decay of ^{160}Re is predicted to be $\sim$300 ms [11], so its effect on the branching ratios is assumed to be negligible.

IV. DISCUSSION

The measured branching ratios and half-life for the ground state of ^{160}Re allow the partial half-lives for the proton and α-decay branches to be deduced. The resulting values are 687 ± 11 μs for proton decay and 5.6 ± 0.5 ms for α decay. The former value is still compatible with proton emission from a $d_{3/2}$ orbital [7], while the latter value allows a more precise reduced α-decay width of 26 ± 3 keV to be deduced using the method of Rasmussen [12] and assuming s-wave α-particle emission. This value for ^{160}Re is somewhat lower than the corresponding values for its nearest odd-odd isotope ^{162}Re (48 ± 7 keV) and isotone ^{158}Ta (31 ± 5 keV) [3], possibly indicating different ground-state spins for ^{156}Ta and ^{160}Re. In Ref. [13] a possible spin-parity assignment of 4^- was suggested for the ground state of ^{160}Re, while a 2^- assignment might be expected for ^{156}Ta [14]. In this scenario involving d-wave emission, the reduced width would be 47 ± 5 keV.

A spectroscopic factor of 0.23 ± 0.04 is deduced for the $\pi d_{3/2}$ state in ^{160}Re using the WKB approximation and the global optical model potential of Becchetti and Greenlees [15]. This value is close to the spectroscopic factor of 0.25 calculated in the BCS theory using the proton pairing strength from Ref. [16] and proton single-particle energies from Ref. [17]. However, it is in clear disagreement with the value of 0.44 expected from a low-seniority shell model calculation [3]. Using the particle-vibration coupling calculation for ^{160}Re presented in Ref. [1], a spectroscopic factor of 0.40 ± 0.01 is obtained, which is similar to the low-seniority shell model value.

In the case of ^{156}Ta, the spectroscopic factor obtained using the WKB approximation is 0.40 ± 0.07, which compares with the expected values of 0.49 using the BCS method and 0.56 using the shell model approach. Unfortunately, calculations for this state are not presented in Refs. [1,2] because of ambiguities arising from the unknown β-decay branch which have only been resolved in the present study. It would clearly be of interest to compare such calculations with these new data and to search for proton emission from $\pi d_{3/2}$ states in other nuclei in this region, such as ^{164}Ir, whose decays should be observable using current experimental techniques [18]. These results could indicate whether there is scope for further improvement in the theoretical descriptions by taking into account pairing effects and particle-vibration coupling of the unpaired neutron, for example [1].

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