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Isomeric proton emission from the drip-line nucleus ^{156}Ta

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A new proton emission line has been observed in the nucleus ^{156}Ta using the fusion reaction ^{58}Ni$+^{102}$Pd$\rightarrow^{160}$W*, $E_x \simeq 61$ MeV. The line has a proton energy $E_p = 1103 \pm 12$ keV corresponding to a Q value $Q_p = 1110 \pm 12$ keV, and a half-life of 320 ± 80 ms. The proton line is assigned to a $\sim 3\%$ decay branch from a high spin $\pi h_{11/2} \nu f_{7/2}$ isomeric state on the basis of systematics. The subsequent implications for level ordering in this region beyond the proton drip line are discussed.

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Proton radioactivity represents an essentially simple quantum tunneling process. In regions of spherical nuclei, where the orbital angular momentum of the odd proton is well defined, proton radioactivity transition rates can be used to identify single-particle shell model orbitals. This approach has been used to assign transitions from the heaviest known proton emitters ^{156}Ta ($Z=73$) and ^{160}Re ($Z=75$) [1]. In Ref. [1] the proton decay of ^{156}Ta was identified using correlations with a weak α-decay branch from the proton emitting state in ^{160}Re, $b_\alpha \simeq 10\%$. Consequently, the ^{156}Ta statistics were much poorer than those available for the ^{160}Re proton decay which was directly populated by a fusion evaporation reaction. However, in both cases it was possible to establish using a WKB analysis that the proton originated from a $d_{3/2}$ orbital. In the case of ^{160}Re the nonobservation of an additional α-decay component from a different state was used to infer that the proton-decaying state represented the ground state of ^{160}Re. However, ^{156}Ta has a neutron number $N=83$ and α decay is inhibited across the $N=82$ major shell closure, hence the competing process would be β decay. As the experiment was insensitive to β decays no conclusion could be drawn as to whether proton emission occurred from the ground state. Earlier work by Hofmann *et al.* producing ^{156}Ta directly in a fusion evaporation reaction indicated the presence of a β-decaying state in ^{156}Ta with a half-life of $t_{1/2} > 10$ ms [2]. This was attributed to the favored Gamow-Teller transition between the configurations $\pi h_{11/2} \nu f_{7/2}{}^{9+} \rightarrow \nu h_{9/2} \nu f_{7/2}{}^{8+}$ on the basis of systematics of odd-odd $N=83$ isotones [3]. The present paper seeks to reconcile the observation of both proton and β decays from ^{156}Ta.

In the present experiment a 6 nA (particle) beam of 290 MeV ^{58}Ni ions was used to bombard a 1 mg cm^{-2} thick target of ^{102}Pd for a period of 30 hours. This produces the compound nucleus ^{160}W* with a center of target excitation energy of $\simeq 61$ MeV, which is expected to correspond to the peak of the excitation function of the $1p3n$ evaporation channel associated with the direct production of ^{156}Ta; this was the same reaction used in [2]. The Daresbury Recoil Mass Separator was adjusted to focus $A=155-158$ evaporation residues onto the focal plane. These ions were implanted into a double-sided silicon strip detector where their subsequent decays could be measured [4].

Figure 1(a) shows the energy spectrum of all decays measured at the focal plane. The broad continuum at lower energies corresponds to α particles which escape

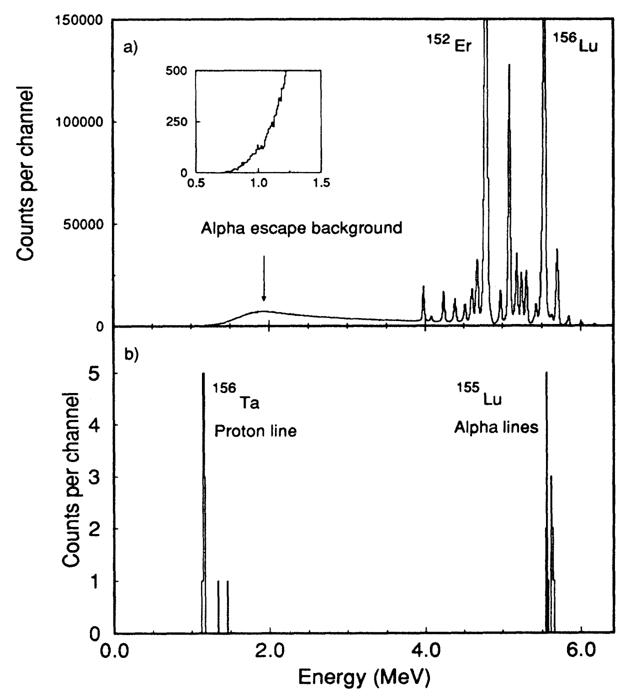

FIG. 1. (a) Energy spectrum of all decays measured at the focal plane; the inset shows the level of the alpha escape background in the energy range characteristic of proton decay. (b) Energy spectrum showing correlated ^{156}Ta ($E_p = 1103 \pm 12$ keV) and ^{155}Lu ($E_\alpha = 5648 \pm 5$ keV and $E_\alpha = 5579 \pm 5$ keV) events. The spectrum shows decay events of 500–1600 keV which are followed by a ^{155}Lu α decay within a time gate of 300 ms $< t <$ 1.5 s on the same detector pixel in the $A=156$ region of the separator focal plane. The first of these decay events must also occur within 1 s of an implanted ion being detected on that pixel.

through the front surface of the strip detector without depositing all their energy. This continuum will completely obscure the direct observation of proton decay lines which have a characteristic energy of $\simeq 1$ MeV in this region. However, the proton decay of ^{156}Ta will populate the β-decaying nucleus ^{155}Hf ($t_{1/2}=890\pm120$ ms [5]) which in turn populates ^{155}Lu. There are three known α transitions from ^{155}Lu; two are associated with low-lying levels ($E_\alpha=5648\pm5$ keV, $t_{1/2}=70\pm6$ ms and $E_\alpha=5579\pm5$ keV, $t_{1/2}=140\pm20$ ms) and the third with a high spin isomeric state ($E_\alpha=7379\pm15$ keV, $t_{1/2}=2.6\pm0.07$ ms) [2,6]. Correlations can therefore be made between proton decays from ^{156}Ta and second generation α decays from ^{155}Lu. Figure 1(b) shows an energy spectrum in which correlated ^{156}Ta and ^{155}Lu decays are incremented. The main gate conditions used to obtain the spectrum shown in Fig. 1(b) were (1) that the initial decay had an energy in the range 500–1600 keV and occurred within 1 s of an implanted ion entering the same detector pixel in the $A=155$ region of the focal plane, and (2) that the ^{155}Lu α decay occurred within a time window of 300 ms $<t<1.5$ s of a preceding decay event on the same pixel; the minimum time condition is associated with the delay in feeding ^{155}Lu through the β decay of ^{155}Hf. It should also be noted that correlations were only found with the two lower energy ^{155}Lu α decays ($E_\alpha=5648$ keV, 5579 keV); none were found with the high-energy isomeric transition ($E_\alpha=7379$ keV). Figure 1(b) clearly reveals the presence of a proton decay line from ^{156}Ta at an energy of $E_p=1103\pm12$ keV with a corresponding Q value of $Q_p=1110\pm12$ keV, calibrated with respect to the known proton decay line ^{147}Tm, $E_p=1051\pm3$ keV [7] produced in a calibration reaction using a ^{92}Mo target. The energy is clearly different to the previously identified proton decay line from ^{156}Ta, $E_p=1022\pm13$ keV which was produced via the α decay of ^{160}Re. This latter line was calibrated with respect to the known proton decay from ^{151}Lu, $E_p=1233\pm3$ keV [7]. Based on these calibration points (which have been calibrated with respect to each other [7]) it is clear that the proton decay line produced directly in the fusion evaporation reaction is not from the same state as that produced via the α-decaying branch of ^{160}Re, albeit that the half-life of the new line $t_{1/2}=320\pm80$ ms is not in disagreement with the value obtained in the earlier experiment: $t_{1/2}=165^{+165}_{-55}$ ms.

Table I shows a comparison of the measured half-lives of the new proton transition with WKB calculations performed using the Becchetti-Greenlees optical potential [8] assuming a spectroscopic factor of unity. The $s_{1/2}$, $d_{3/2}$, and $h_{11/2}$ proton orbitals are all expected to lie close to the Fermi surface in this region. From the table it is clear that the $s_{1/2}$ and $d_{3/2}$ orbitals can be excluded as an origin of this activity as the predicted half-lives are too short by orders of magnitude, and no hindrance effects are anticipated in this region. However, the calculation for the $h_{11/2}$ proton orbital is $\simeq 40$ times greater than the measured value, indicating that β decay represents the dominant branch for this state. Fortunately, excellent systematics for odd-odd $N=83$ isotones are available for favored Gamow-Teller transitions between $\pi h_{11/2}\nu f_{7/2}{}^{9+}\rightarrow\nu h_{9/2}\nu f_{7/2}{}^{8+}$ states [3]. These systematics, which extend to the neighboring odd-odd $N=83$ isotone ^{154}Lu, indicate a $\log ft$ value of $\simeq 3.0$ for the corresponding transition in ^{156}Ta which gives a predicted half-life of $t_{1/2}\simeq 400$ ms (extrapolating energy level systematics). This is in good agreement with the measured half-life in the present experiment and is consistent with the lower limit of 10 ms suggested by Hofmann *et al.* [2] for this transition. It is also consistent with the data from [3] in which only the β decay from high spin $\pi h_{11/2}\nu f_{7/2}{}^{9+}$ isomeric states in odd-odd $N=83$ isotones is observed in heavy-ion fusion evaporation reactions. The production cross section for the new line is $\simeq 50$ nb (corresponding to an estimated recoil separator efficiency of $\simeq 3\%$), which is considerably lower than the measured cross sections of $\sim\mu$b observed for previous $1p3n$ channels in this region [9], indicating that a depletion of the yield has occurred through β decay. On this overall basis we therefore assign the new proton line to the decay of a $\pi h_{11/2}\nu f_{7/2}{}^{9+}$ isomeric state in ^{156}Ta (although coupling to a 7^+ or 8^+ state cannot be ruled out, as will be discussed) with a corresponding branching ratio $b_p\sim 3\%$ based on the partial half-life prediction for $h_{11/2}$ proton emission shown in Table I. Furthermore, on the basis of the systematics in [3] we can now assign the previously observed proton transition to the decay of the

TABLE I. Comparison of the measured half-life of the new proton decay line from ^{156}Ta with WKB calculations using a Becchetti-Greenlees potential [8]. Spectroscopic factors of unity have been assumed in all cases.

^{156}Ta proton energy	Proton decay half-life			
	Experiment	$h_{11/2}$	$d_{3/2}$	$s_{1/2}$
1103±12 keV	320±80 ms	11 s	5 ms	550 μs

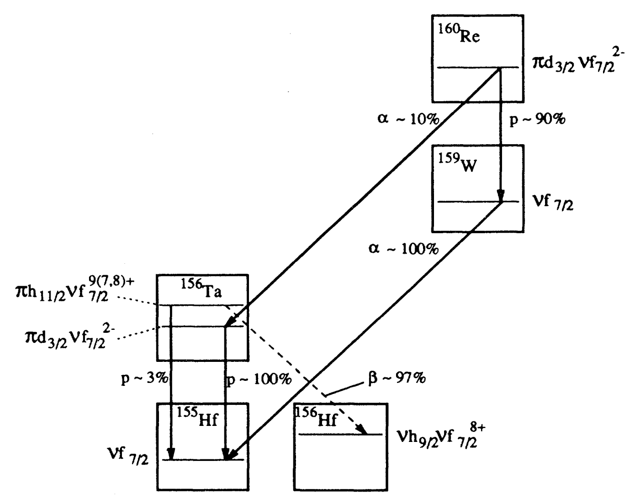

FIG. 2. Decay scheme showing the unique proton-alpha decay Q-value loop between the ground states of ^{160}Re and ^{155}Hf. Measured alpha and proton transitions are denoted by solid lines and the dashed line represents the estimated β branch from the high spin isomeric state in ^{156}Ta at an excitation energy of 81±17 keV.

$\pi d_{3/2}\nu f_{7/2}{}^{2-}$ ground-state level in ^{156}Ta. In each case the nucleus will most likely decay to a $\nu f_{7/2}$ ground-state level in ^{155}Hf. The nonobservation of the $\pi h_{11/2}\nu f_{7/2}{}^{9+}$ level in ^{156}Ta populated via the α decay of ^{160}Re [1] is most probably associated with configuration hindrance in going from a $\pi d_{3/2}$ orbital in the parent nucleus ^{160}Re to a $\pi h_{11/2}$ proton orbital in the residual nucleus. In addition the greater Q value will favor α decay to the $\pi d_{3/2}\nu f_{7/2}{}^{2-}$ ground state. The proposed decay scheme showing the closed Q-value loop between ^{160}Re and ^{155}Hf is summarized in Fig. 2.

The present data imply that the $\pi h_{11/2}\nu f_{7/2}{}^{9+}$ isomeric state lies at an excitation energy of 81 ± 17 keV with respect to the $\pi d_{3/2}\nu f_{7/2}{}^{2-}$ ground state in ^{156}Ta. It is interesting to note that previous measurements of odd-odd $N=83$ isotones lying closer to stability have been unable to establish the relative ordering of these levels, let alone the excitation energy [10]. This new information can potentially be used for shell model calculations in the region of nuclei above the double shell closure nucleus ^{146}Gd for $N>82$ [11]. However, it must be mentioned that work by Vierinen *et al.* [12] suggests that the odd neutron and proton in the neighboring $N=83$ nucleus ^{154}Lu may couple to form a 7^+ isomer rather than the 9^+ assignment implied by the systematics of [3], while the shell model calculations of Kleinheinz *et al.* [11] suggest that a $\pi h_{11/2}\nu f_{7/2}{}^{8+}$ isomeric state may be formed in ^{156}Ta.

In summary, a new proton decay line has been identified from a high spin isomer in the drip-line nucleus ^{156}Ta. This measurement has shown the value of proton radioactivity as a spectroscopic tool at the extreme edge of nuclear stability. It is noteworthy that isomeric proton emission has now been identified in four (^{53}Co, ^{146}Tm, ^{147}Tm, ^{156}Ta) out of the nine known isotopes exhibiting proton radioactivity.

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