Identification of excited states in ^{140}Dy

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Abstract

Excited structures in the proton-rich nucleus ^{140}Dy have been established following the decay of an 8^- isomer. The excitation energy of the isomer is established to be 2.16 MeV with a half-life of 7.3 ± 1.5 μs. The isomer decays into the yrast line at the 8^+ state, revealing a rotational band with a deduced deformation of $\beta_2 = 0.24(3)$. The isotope ^{140}Dy is the daughter of the deformed proton emitter ^{141}Ho. The new information obtained here supports the role of deformation in proton emission and the previous assignments of single-particle configurations to the two proton emitting states in ^{141}Ho. In addition, the reduced hindrance factor measured for the isomer is consistent with the trend observed in the $N = 74$ isotones. © 2002 Elsevier Science B.V. All rights reserved.

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The proton drip line can be readily delineated, above $Z = 50$, by nuclei which decay by the emission of a proton. So-called proton emitters have by now been identified in almost all odd-Z systems from Sb ($Z = 51$) to Bi ($Z = 83$) [1]. In most instances, proton emission can be understood in terms of simple quantum tunneling through a one-dimensional barrier from a spherical nucleus. Hence, proton decay has become a potent spectroscopic tool to characterize states located near the Fermi surface in nuclei at the very limits of stability.

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Recently, proton radioactivity has been observed in ^{141}Ho and ^{131}Eu [2]. Based on the measured half-lives, the proton emitting states have been interpreted as requiring the presence of a sizeable quadrupole deformation, and the decay rates have been reproduced using, for example, the multiparticle theory of proton emission from deformed nuclei by Bugrov and Kadmensky [3]. In ^{131}Eu, additional information was obtained by observing not only proton decay to the ground state of the daughter nucleus, ^{130}Sm, but also to the first excited 2^+ level [4]. By utilizing both the excitation energy of the 2^+ state and the branching ratio, the spin and intrinsic configuration of the proton emitting state could be determined unambiguously[4]. In ^{141}Ho, no such decay to the 2^+ level has been observed so far, and the assignment of the $7/2^-$[523] and $1/2^+$[411] Nilsson configurations to the ^{141}Ho ground and isomeric states, respectively, was deduced solely from the measured decay rates [2, 5]. Confirmation of sizeable deformation as well as complementary information on the structure of these states was obtained from in-beam γ-ray studies utilizing the Recoil Decay Tagging (RDT) technique where rotational bands were established on top of both proton-emitting states [6]. The deduced deformations, $\beta_2 \sim 0.25(4)$, are consistent with those inferred from the proton decay rates. Furthermore, an analysis of the moments of inertia for each band also supports the single-particle configurations proposed from the proton-emission work.

While both the configuration and deformation of the ^{141}Ho proton-emitting states are consistent with the results of the in-beam γ-ray study, critical information about the ^{140}Dy daughter nucleus is still missing. Proton emission to the 2^+ level in ^{140}Dy has not been observed, however, an upper limit for the branching ratio between the 2^+ and 0^+ feedings into ^{140}Dy has been placed at 1% [6] for decays from the assigned $7/2^-$ ^{141}Ho, ground state. Based on this limit, calculations using the adiabatic formalism of Ref. [7] place a lower limit of ~ 190 keV for the excitation energy of the 2^+ state in ^{140}Dy.

Among the surprises of the in-beam RDT studies [6] is the observed large energy (signature) splitting between the favored and unfavored band partners which has been viewed as indicative of the onset of sizeable Coriolis mixing. It has been suggested that this mixing results from shape polarization imposed

by the odd proton when it occupies the $7/2^-$[523] orbital [6]. Interestingly, coupled channel calculations, which include the effects of Coriolis mixing, estimate the spectroscopic factor to be 3.2 [7] and 4.9 [8] for the proton decay of the ground state. This should be compared with the more reasonable value of 0.66 deduced within the adiabatic approximation [7] where Coriolis mixing is not explicitly considered. Thus, the model which best reproduces the observed lifetimes and the data on excited states seem to contradict one another. One possible explanation is that there is little Coriolis mixing in the ground state and that it is induced at higher-spins by rotation. To investigate this further and to confirm the implicit theoretical assumption that both the parent and daughter have the same deformation, it would be useful to measure the yrast band of ^{140}Dy, in order to establish the excitation of the 2^+ level as well as to deduce the associated deformation. The isotope, ^{140}Dy is, however, difficult to study with conventional in-beam γ-ray spectroscopy, because its production cross section using heavy-ion fusion evaporation reactions is small and of order, $\sigma \leqslant 10$ μb. The problem of small cross sections was overcome for ^{141}Ho by utilizing the RDT technique, a powerful method which correlates prompt-γ radiation with the characteristic charged-particle decay of the nucleus of interest [6]. Unfortunately, ^{140}Dy decays only via β^+ emission and, thus, the RDT technique cannot be applied for in-beam studies of this isotope.

Recently, Cullen et al. [9] suggested that the yrast band of ^{140}Dy could be identified at least up to the 8^+ level by measuring γ rays emitted following the decay of a predicted $K^\pi = 8^-$ isomer. Indeed, a number of high-K isomers has been identified in the $N = 72$–74 isotones. For example, $K^\pi = 8^-$ isomeric states are known in all of the even–even $N = 74$ isotones, $^{128}_{54}$Xe [10], $^{130}_{56}$Ba [11], $^{132}_{58}$Ce [12], $^{134}_{60}$Nd [13], $^{136}_{62}$Sm [14] and $^{138}_{64}$Gd [15]. The associated half-lives range from nanoseconds (Xe) to milliseconds (Ba, Ce). Recent calculations [16] have predicted the presence of a similar $K^\pi = 8^-$ isomeric state in ^{140}Dy with an excitation energy of 2.15 MeV and a deformation $\beta_2 = 0.26$. The measurement of the isomer's half-life and excitation energy is also interesting in this instance as it provides one of the few tests of the applicability of the concept of K-forbiddenness at the proton drip line and gives additional information about the shape of ^{140}Dy. In this Letter, we report the identification of the $K^\pi = 8^-$

isomer in ^{140}Dy at 2.16 MeV, and its subsequent decay by γ emission to the ground state. The half-life of the isomer is measured to be 7.3 ± 1.5 µs, and the excitation energy of the 2^+ state is 202 keV.

In order to populate and identify states following the decay of the $K^\pi = 8^-$ isomer in ^{140}Dy, a 245 MeV beam of ^{54}Fe ions from the ATLAS accelerator, at Argonne National Laboratory, was directed on a self-supporting, 550 µg/cm^2 foil of ^{92}Mo ($> 90\%$ enriched). A 5 µg/cm^2 thick carbon foil was located behind the target to reset the charge state distribution of the recoiling evaporation residues. The latter were then sent through the Argonne Fragment Mass Analyzer (FMA) [17] and were dispersed according to their mass-to-charge (M/q) ratio at the focal plane of this instrument. A position-sensitive, parallel grid avalanche counter (PGAC), located at the focal plane, provided the M/q information as well as the time of arrival and energy-loss signals of the evaporation residues. The recoiling nuclei were subsequently implanted into a large area silicon detector located 40 cm behind the PGAC. Surrounding this Si detector were 7 HPGe detectors of various sizes and efficiencies. A 70% efficient, co-axial detector was placed directly behind the Si detector. Four $\sim 25\%$ co-axial detectors of the so-called "golf club" configuration were mounted at $\sim 90°$ to the beam, $\sim \pm 45°$ from the horizontal plane. Two planar Ge detectors were located at $\sim 90°$ with respect to the beam and $\pm 90°$ with respect to the horizontal plane. A valid trigger consisted of a PGAC-Si coincidence and a γ ray detected within 80 µs of the implantation of a residue into the Si detector.

With this ^{54}Fe $+ ^{92}$Mo reaction at 245 MeV, ^{140}Dy is produced via the $\alpha, 2n$ evaporation channel. In addition, mass 140 isobars represent only $\sim 5\%$ of the fusion-evaporation cross section at this beam energy while the two dominant masses are $A = 142$ and 143. In order to minimize contributions from other reaction channels, slits were placed in front of the PGAC, allowing only 2 charge states of mass 140 residues to be detected at the focal plane. As a result, a beam intensity as high as 20 pnA was accommodated.

The total γ-ray spectrum measured in the experiment is given in Fig. 1(a). Besides the dominant annihilation line at 511 keV, most of the remaining transitions can be associated with the β decay of ^{140}Tb, ^{140}Gd, ^{140}Eu and ^{140}Sm. These transitions appear in

the spectrum due to random coincidences between the implanted ions and the γ rays following β decay. Fig. 1(b) shows a γ-ray spectrum measured within 10 µs after the arrival of a residue in the Si detector. In this case, the random coincidences have been subtracted from the total spectrum. Most of the strongest transitions arise from the decay of a 15 µs isomer in ^{142}Tb [18,19] and the decay of a 0.5 µs isomer in ^{144}Ho [19]. For the ^{142}Tb case, the isomeric state is strongly populated at this beam energy and is observed in the data due to tails in the mass distribution which overlap with the $A = 140$ mass peaks. For the ^{144}Ho, its production most likely results from reactions involving ^{94}Mo which are present in the target at the $\sim 2\%$ level. The unidentified γ rays in the spectrum are candidates for transitions following the isomer decay in ^{140}Dy. The analysis of the γ-ray coincidence matrix produced with the requirement that the γ rays were emitted within 20 µs of the detection of an implanted ion yielded a set of five γ rays (202.1, 363.2, 475.8, 549.4, and 573.6 keV) in coincidence with one another. A spectrum produced from a sum of coincidence gates placed on all five transitions is shown in Fig. 1(c). These γ rays are weak but discernible in Fig. 1(b).

The time spectrum between the arrival of a residue at the Si detector and the subsequent coincident emission of any two of the five γ rays is given in Fig. 2(a). A fit to these data indicates that these transitions follow the decay of an isomer with a half-life of 7.3 ± 1.5 µs. This value compares well with the systematic trend of the lifetimes of the $K^\pi = 8^-$ isomeric states across the $N = 74$ chain, which results in an anticipated lifetime of ~ 6 µs for the $K^\pi = 8^-$ isomer in ^{140}Dy. The M/q spectrum associated with these five transitions is shown in the top panel of Fig. 2(b). It was produced under the same conditions as the time spectrum in Fig. 2(a). The bottom panel of Fig. 2(b) gives the M/q spectrum associated with the ^{142}Tb isomer (dashed line) whose γ rays are marked in Fig. 1(b). Also shown as a solid line is the total M/q spectrum when the slits are removed. The spectrum in the top panel conforms nicely, both in shape and in width, with the $A = 140$ peaks observed in the total M/q spectrum, thus confirming that the γ transitions from Fig. 1(c) belong to a residue with mass 140. In contrast, the M/q spectrum for the ^{142}Tb isomer (dashed line) is much broader and fills up the entire area al-
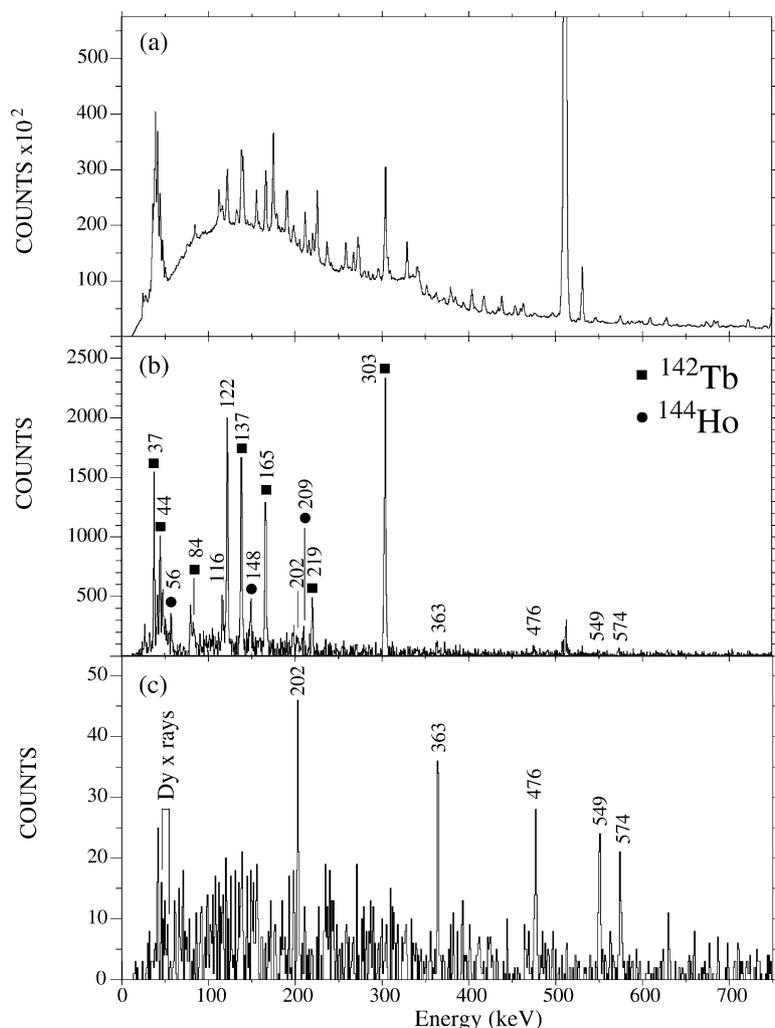
Fig. 1. (a) The total γ-ray spectrum measured in this experiment. Besides the dominant 511-keV, annihilation line, most of the remaining transitions can be associated with the β decay of ^{140}Tb, ^{140}Gd, ^{140}Eu and ^{140}Sm. (b) A spectrum of γ rays measured within the first 10 μs following the arrival of a residue in the Si detector. The contribution from random coincidences has been subtracted. (c) A spectrum produced from a sum of coincidence gates placed on the 202.1-, 363.2-, 475.8-, 549.4-, and 573.6-keV transitions in a matrix produced with the requirement that the γ rays were emitted within 20 μs of the detection of an implanted ion.

lowed by the slits, as expected for tails from the ^{142}Tb mass peaks. While there is some evidence for co-incidences between the five γ lines and Dy X rays (Fig. 1(c)), the statistics are not sufficient to provide an unambiguous ^{140}Dy assignment. Nevertheless, the observed yield is consistent with that expected from the internal conversion process assuming an E2 mul-tipolarity for the first four transitions (note that nearly all this X-ray yield originates from the lowest energy

transition at 202.1 keV). Fig. 2(c) presents the pro-posed ordering of the γ rays assuming that they origi-nate from the decay of the expected $K^{\pi} = 8^-$ isomer in ^{140}Dy. The placement of the 549.4- and 573.6-keV transitions could be transposed. Arguments in favor of the current placement are given below. Fig. 3 illus-trates the systematic trend for the 0^+, 2^+, 4^+, 6^+, 8^+ and $K^{\pi} = 8^-$ states across the known $N = 74$ chain, from ^{130}Ba to ^{138}Gd, together with the proposed se-
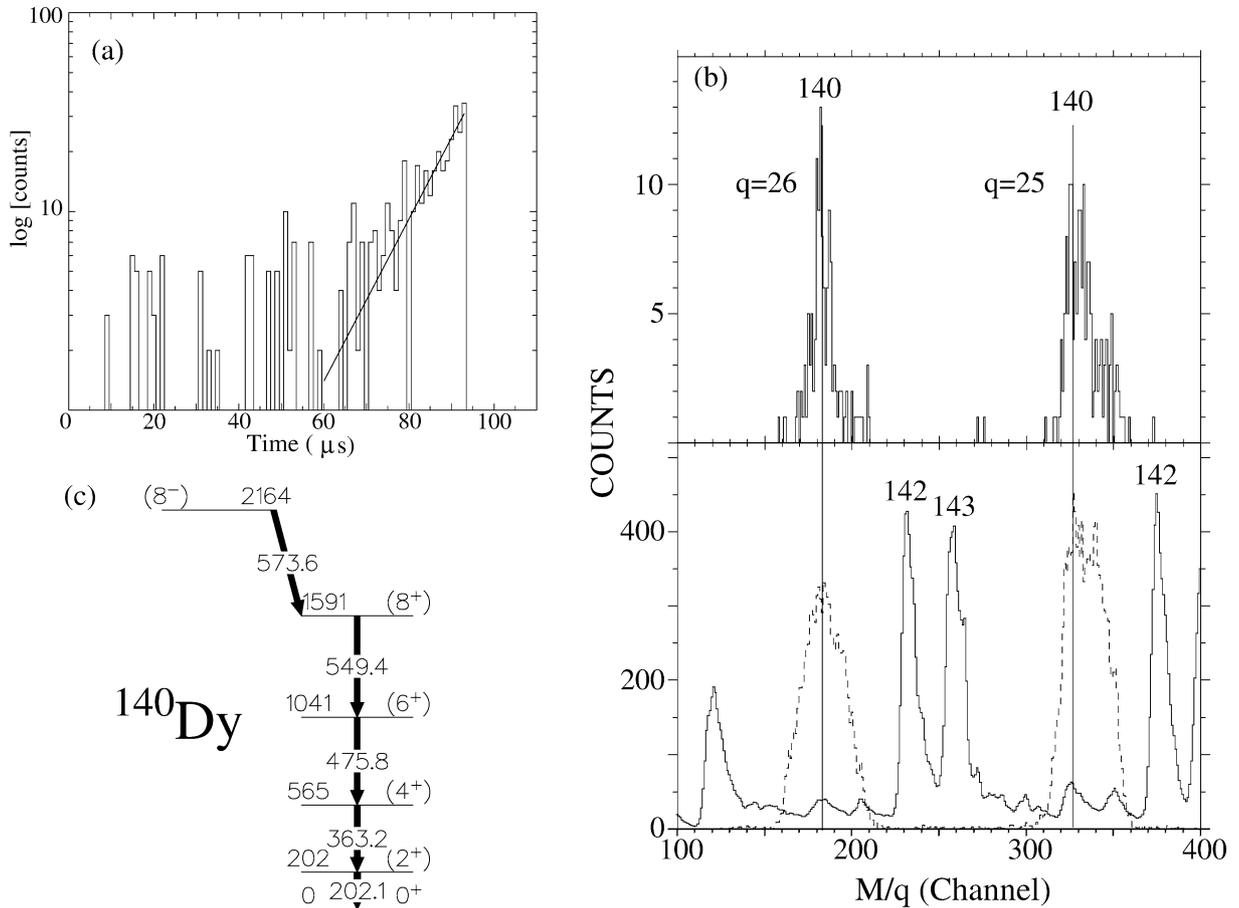
Fig. 2. (a) Time delay between the implant of a residue and the detection in prompt coincidence of any two of the five γ rays of Fig. 1(c). The solid line represents a fit to the data which yields a half-life of 7.3 µs. (b) Top panel: M/q spectrum measured at the FMA focal plane when requiring the detection of an implanted ion followed within 20 µs by any two of the five γ rays of Fig. 1(c) in prompt coincidence (mass slits in place). Bottom panel: the dashed-line histogram is the M/q spectrum observed when requiring γ rays in ^{142}Tb to be measured within 20 µs of the detection of an implanted ion (mass slits in place). The solid-line histogram is the observed total M/q spectrum when the mass slits are removed. (c) Proposed level sequence following the decay of the $K^\pi = 8^-$ isomer in ^{140}Dy.

quence of Fig. 2(c). It can be seen that the new points continue the smooth trend exhibited by earlier data. This observation together with the lifetime and the association with a mass 140 residue, leads us to assign the isomer and its subsequent decay to ^{140}Dy.

The deformation of the ground-state band in ^{140}Dy can be estimated using the approach proposed by Grodzins [20] which requires only the excitation energy of the first 2^+ state and the mass number of the nucleus as input. The deduced deformation for ^{140}Dy is $\beta_2 = 0.24$, a value which is close to that obtained with the same method for ^{138}Gd; $\beta_2 =$

0.237. In addition, the deformation of the daughter, calculated with the Grodzins prescription, is nearly the same as that extracted from the rotational band built on the ground state in ^{141}Ho ($\beta_2 = 0.25(4)$) [6]. Recent Woods–Saxon constrained shape polarization calculations [16] predict the existence of a $K^\pi = 8^-$ isomeric state in ^{140}Dy at an excitation energy of 2150 keV with a deformation $\beta_2 = 0.26$. Thus, the experimental excitation energy of 2164 keV and the associated deformation of $\beta_2 = 0.24(3)$ are in good agreement with these theoretical expectations.
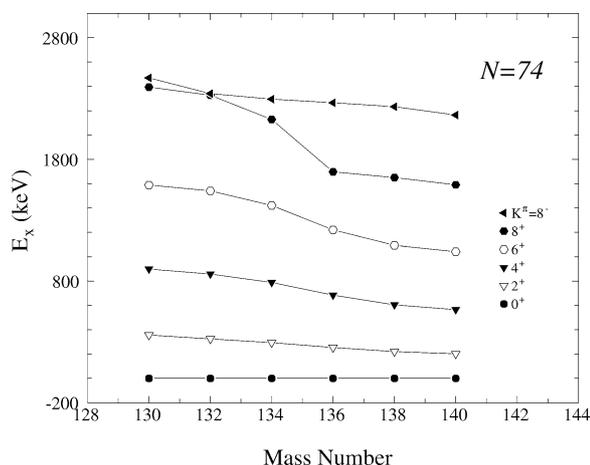
Fig. 3. The excitation energies of the $K^\pi = 8^-$ isomeric states and the yrast bands for the $N = 74$ isotones from ^{130}Ba to ^{140}Dy. The new values for ^{140}Dy continue the rather slow and smooth decrease with increasing mass from ^{136}Sm to ^{138}Gd.

Fig. 4. The dynamical moments of inertia, $J^{(2)}$, as a function of rotational frequency for the two rotational bands identified in ^{141}Ho [6], the yrast band of ^{138}Gd [22], and the newly identified yrast band of ^{140}Dy, see text for details.

The branching ratio between the proton decay from the $7/2^-$ state in ^{141}Ho to the ground state and first 2^+ state in ^{140}Dy has been calculated with the adiabatic formalism of Ref. [7]. In the calculations, values of $\beta_2 = 0.244$, obtained from the Grodzins formula, and $\beta_4 = -0.046$, scaled from the Möller prediction, were used for ^{140}Dy. (Möller et al. [21] predict deformations $\beta_2 = 0.267$ and $\beta_4 = -0.05$ for ^{140}Dy.) The resulting branching ratio is 0.7%, consistent with the experimental upper limit of 1% obtained in Ref. [6]. As mentioned above, in the study of ^{131}Eu this branching ratio enabled a determination of the intrinsic configuration of the proton emitting state. Such information was required, because the decay rates for the two candidate configurations were, by chance, nearly the same while the calculated branching ratios differed significantly. For ^{141}Ho, the measured decay rates led to an unambiguous assignment of the configurations to the two proton emitting states [2,5]. In the study of excited structures built upon these states [6], the moments of inertia of the observed bands were compared with those of similar configurations in lighter nuclei. It was noted that the behavior of the bands as a function of rotational frequency was consistent with the configurations proposed in the proton decay work. With the identification of the rotational band in ^{140}Dy, a direct compar-
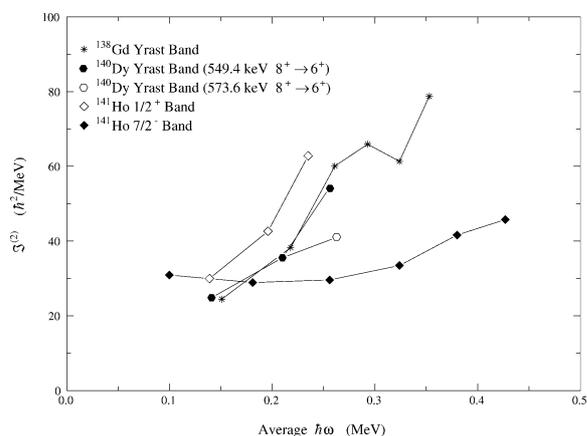
ison of the rotational properties of the two bands in ^{141}Ho with those of the even-even core is now possible.

Fig. 4 presents the dynamical moments of inertia, $J^{(2)}$, as a function of rotational frequency for the two rotational bands identified in ^{141}Ho [6], the yrast band of ^{138}Gd [22], and the newly identified yrast band of ^{140}Dy. For the case of ^{140}Dy, the two data points at the highest rotational frequency represent the assignment of either the 549.4-keV or the 573.6-keV transition to the $8^+ \rightarrow 6^+$ transition. As mentioned above, it is not possible to determine the ordering of these two transitions from the current data. There is a marked difference in the evolution of the $J^{(2)}$ moment for the two ^{141}Ho bands. The nearly constant moment of inertia for the ^{141}Ho ground state band was cited as confirming evidence for a $h_{11/2}$ assignment, as it is brought about by the blocking of the alignment of a pair of $h_{11/2}$ quasiprotons. In contrast, the rise of the $J^{(2)}$ moment in the band built on the isomer has been attributed to such a proton $h_{11/2}$ alignment, and this is consistent with the $1/2^+[411]$ assignment suggested from the proton decay rates. The yrast band of ^{138}Gd exhibits a behavior similar to that of the $1/2^+[411]$ band over the same frequency range. For the case of ^{140}Dy, the level scheme as presented in Fig. 2(c) results in a $J^{(2)}$ moment which is nearly identical to that of ^{138}Gd. If the ordering of the 549.4- and

Table 1
Systematics of reduced hindrance factors, f_ν, for observed E1 decays from $K^\pi = 8^-$ isomers in the $N = 74$ isotones [15]. The value for ^{140}Dy is from this work

Nucleus	$T_{1/2}$	f_ν
$^{130}_{56}$Ba	112 ± 2 ms	43.5
$^{134}_{60}$Nd	410 ± 30 μs	26.1
$^{136}_{62}$Sm	15 ± 1 μs	24.9
$^{138}_{64}$Gd	6 ± 1 μs	24.1
$^{140}_{66}$Dy	7.3 ± 1.5 μs	24.6

573.6-keV transitions is transposed, a more gentle rise of the $J^{(2)}$ moment is observed, suggesting a delay in the rotational alignment of the $h_{11/2}$ quasiproton pair. This effect is not a priori an unreasonable expectation because of the increase in the deformation and the moving of the Fermi surface higher in the $h_{11/2}$ subshell. It is, however, not supported by the behavior of the $1/2^+[411]$ band in ^{141}Ho whose placement at the Fermi surface and whose associated deformation are nearly identical to those of ^{140}Dy. Based on these observations, the ordering of the transitions presented in Fig. 2(c) appears to be most consistent with the rotational properties observed in neighboring nuclei and is adopted here as the most likely.

In order to compare the isomeric decay of the $K^\pi = 8^-$ state in ^{140}Dy with the decays of other $K^\pi = 8^-$ isomers in the neighboring $N = 74$ isotones, the reduced hindrance factor, f_ν, has been calculated. This factor is defined as

$$f_\nu = \left\{ T_{1/2}^\gamma / T_{1/2}^W \right\}^{1/\nu}, \tag{1}$$

where $T_{1/2}^\gamma$ is the partial γ-ray half-life, $T_{1/2}^W$ is the Weisskopf single-particle estimate, ν is the degree of K forbiddenness, $\nu = \Delta K - \lambda$, and λ is the multipolarity of the transition depopulating the isomeric state. The reduced hindrance per degree of K-forbiddenness for the direct, 573.6-keV, E1 transition from the $K^\pi = 8^-$ isomeric state to the ground-state band in ^{140}Dy is deduced to be 24.6. As can be seen from Table 1, this value is essentially the same as those obtained for all other $N = 74$ even–even isotones, with the exception of ^{130}Ba (see below for a further discussion of this point). The fact that, in addition to the smooth energy systematics of Fig. 3, the f_ν factor is also very close to that of the other $N = 74$ isotones can then be viewed as a clear in-

dication that the interpretation of the new long-lived state as a K isomer is justified, and that the proximity of the proton drip line has little effect upon the stability and properties of this K-isomer. Furthermore, the fact that K is approximately a good quantum number in ^{140}Dy can in turn be regarded as strong experimental evidence for an axially symmetric nuclear shape. This validates the approach used here to extract the prolate deformation parameter and adds credibility to the discussions presented above.

The near equality of the hindrance factors in Table 1 can also be used to propose a configuration for the ^{140}Dy isomer. In the mass 180 region, it has been shown that there is a correlation between the reduced hindrance factors and the configuration changes involved in the decay of similar K-isomers [23–25]. The equality of the hindrance factors, therefore, supports the $7/2^+[404] \otimes 9/2^-[514]$ two-quasineutron configuration for the $K^\pi = 8^-$ isomer in ^{140}Dy, matching the 8^-, ν^2 configuration established in the $N = 74$ isotones, ^{134}Nd [13], ^{136}Sm [14] and ^{138}Gd [15]. As already pointed out by Bruce et al. [15], the larger f_ν value for ^{130}Ba could reflect a change in the configuration and/or possibly in the shape associated with the isomer. Additional confirmation of the configuration of the $K^\pi = 8^-$ isomer in ^{140}Dy could be obtained from M1/E2 branching ratios of the collective rotational band built on the isomer as in Refs. [26,27]. This information is presently not available.

In summary, excited states in the proton-rich nucleus ^{140}Dy have been established following the decay of a $K^\pi = 8^-$ isomeric state. The excitation energy of the isomer is established as 2.16 MeV with a half-life of 7.3 ± 1.5 μs. The isomer decays into the yrast line at the 8^+ state, revealing a rotational band based on an axially symmetric shape with a deduced deformation of $\beta_2 = 0.24(3)$. ^{140}Dy is the daughter nucleus of the deformed proton emitter ^{141}Ho, and the new information obtained in this work supports previous single-particle assignments to the two proton emitting states in ^{141}Ho. Based on the measured 2^+ energy and the deduced deformation, the adiabatic calculation of Ref. [7] predicts a branching ratio for proton decays to the first excited 2^+ state in ^{140}Dy of 0.7%. This value is consistent with the experimental upper limit of 1%. In addition, the reduced hindrance factor deduced for the isomer is consistent with the trend observed in the

$N = 74$ isotones and shows no deviations which could be attributed to the proximity of ^{140}Dy to the proton drip line.

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