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First observation of the drip line nucleus ^{140}Dy: Identification of a 7 μs K isomer populating the ground state band

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A new 7 μs isomer in the drip line nucleus ^{140}Dy was selected from the products of the ^{54}Fe (315 MeV)$+^{92}$Mo reaction by a recoil mass spectrometer and studied with recoil-delayed γ-γ coincidences. Five cascading γ transitions were interpreted as the decay of an $I^{\pi}=8^{-}$ $\{\nu 9/2^{-}[514]\otimes\nu 7/2^{+}[404]\}$ K isomer ($T_{1/2}=7.0(5)$ μs) via the ground-state band. The probability of proton emission from ^{141}Ho to the 0^{+} ground state and to the 2^{+} excited state in ^{140}Dy is discussed.

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The decays of ground and metastable states in nuclei around the proton drip line provide unique information on the nuclear structure at the limits of nuclear stability. Measured properties of direct proton emitters tell us about the mass and shape of the nucleus and about the nature of proton [1,2] and neutron [2–4] orbitals in exotic nuclei. In particular, if fine structure in proton emission is detected [5,2], the individual spherical components of the emitter's wave function can be deduced [6–8]. For complete and consistent analysis of the decay rates and structure of proton unstable nuclei, the excited levels in the emitter and in the daughter nucleus are needed.

The ground state of ^{140}Dy is populated in the decay of deformed proton emitters $^{141\text{g.s.}m}$Ho [9–11]. No spectroscopic information on the ^{140}Dy was available prior to this work. The structure of the p-emitting states in ^{141}Ho as well as the energies of the ground-state band in ^{140}Dy, in particular, the energy of the first 2^{+} level, govern the probability for the yet unobserved fine structure in proton emission from $^{141\text{g.s.}m}$Ho [9–11]. From the properties of the ground-state band in ^{140}Dy one can learn about the quadrupole deformation of the potential tunneled by the emitted protons. The presence of an $I^{\pi}=8^{-}$ metastable level populating the ground-state band in a sequence of neutron-deficient even $N=74$ isotones (see [12–15] and references therein) has prompted the search for such a K isomer in ^{140}Dy [14,16]. Since ^{140}Dy is produced with a very small fraction of the total reaction cross section previous studies led to the conclusion [13,16] that ^{138}Gd is the last $N=74$ isotone that can realistically be studied with a fusion-evaporation reaction using a stable beam and stable target combination. However, the importance of ^{140}Dy structure motivated our search for the ^{140m}Dy, a first K isomer in the daughter of a proton unbound nucleus.

The experiment was performed at the Holifield Radioactive Ion Beam Facility (HRIBF) at Oak Ridge. During a 58-h run a 1 mg/cm^2 target of ^{92}Mo isotopically enriched to 98.7% was bombarded with 315 MeV ^{54}Fe ions accelerated by the HRIBF 25 MV Tandem. An average beam current of about 18 particle nA was maintained with peak values of up to 24 pnA. Fusion-evaporation products were separated by the Recoil Mass Spectrometer (RMS) [17], which was operating in the recoil-diverging mode and optimized for mass $A=140$ products with a charge state of $Q=+27$ and a recoil energy of 92 MeV. The recoils passed through a microchannel plate (MCP) detector [18] placed in the focal plane and were implanted in a passive catcher. The MCP provided a recoil implantation reference time and recoil position signals allowing the mass selection. The catcher was placed behind the RMS focal plane inside the Clover Germanium Detector Array for Recoil Decay Spectroscopy (CARDS). The high selectivity of the RMS allowed us to run with high beam intensity without overloading the final focus detectors with scattered primary beam particles and γ radiation. The mass separation was also crucial for this study since other μs activities are produced more abundantly in the reaction; compare [16,19].

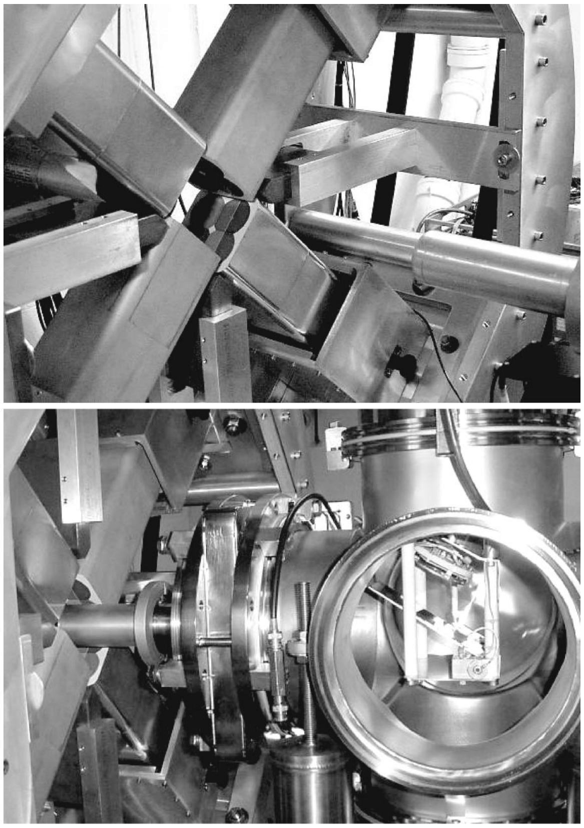

FIG. 1. MCP and CARDS at the final focus of the RMS. The passive catcher was placed inside a thin aluminum nose in the center of the γ array presented in the upper panel. A γX Ge detector was placed at 0°. An MCP placed before the catcher provided the recoil implantation signals (bottom panel). The electron emitting foil and the microchannel plate, both at 45° to the beam, can be seen.

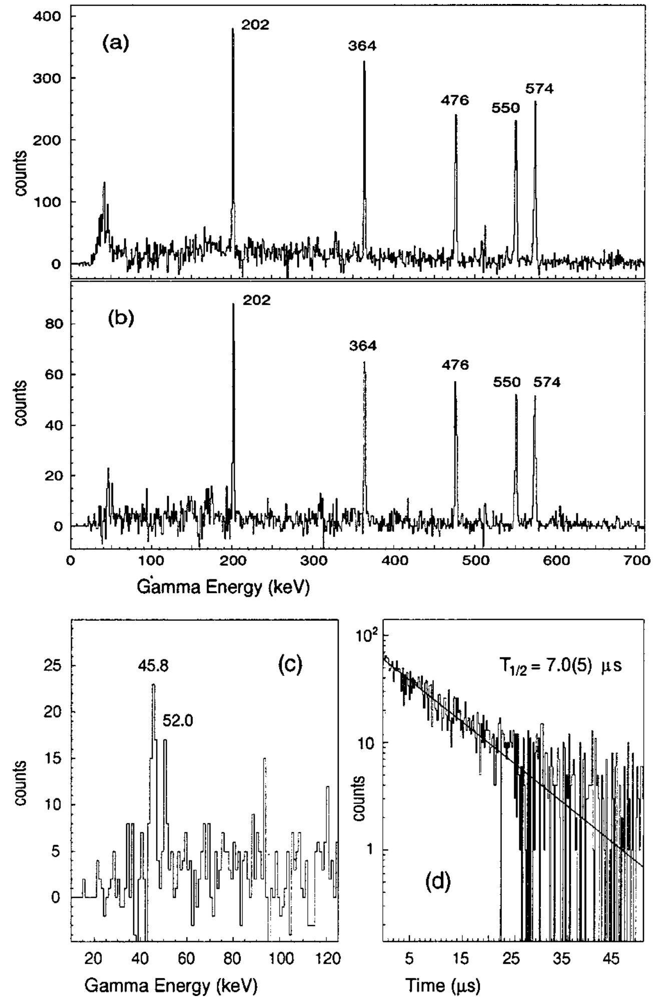

FIG. 2. ^{140}Dy γ lines from the decay of the $I^{\pi}=(8^{-})$ isomer. All γ spectra are calibrated to 1 keV/bin. The spectrum in panel (a) was obtained by adding five spectra gated on the labeled γ transitions (double coincidence data). The spectrum in panel (b) was obtained from triple γ coincidence data by double gating on the labeled transitions. The low energy part of the double-gated spectrum shown in (c) reveals dysprosium K_{α} and K_{β} X rays. The decay pattern produced by double-gating on five transitions is shown in panel (d).

The close geometry CARDS setup was used to measure the energies of the γ rays emitted from recoils stopped in the catcher; see Fig. 1. At the time of the experiment it consisted of four segmented Clover Ge detectors and one γX Ge detector. The detectors were operated without BGO Compton suppression shields and placed about 5 cm from the center of the catcher to maximize the solid angle of detection. Lead and copper shields were placed between neighboring crystals to limit background caused by the cross-talk between the detectors. The total photopeak efficiency was measured using calibrated sources and varied from 14% for 200 keV γ rays to a maximum of 18% around 80 keV, and remained as high as 4% at 1.33 MeV.

All the signals from the γ-ray detectors and MCP counter were processed by Digital Gamma Finder modules (DGF4C) manufactured by XIA [20]. Preamplifier pulses were digitized without prior shaping. The amplitude and real-time of the signals were derived using the on-board Digital Signal Processor and 40 MHz clock. The data were stored in the DGF4C memory buffer before further transfer and analysis. No hardware gate was applied to the collected signals, i.e., they were all counted in time-stamped "singles" mode [21]. With this type of data acquisition, there are no restrictions on the recoil-delayed γ correlation window, which can be applied in the off-line data processing. This allowed us to reduce the γ background caused by both short-lived activities such as the 0.3 μs isomer ^{140m}Eu [22] producing strong γ lines at 98, 171, 191, 253, 362, and 423 keV, and by the long-lived β emitting $A=140$ isobars.

We have identified a new γ cascade of coincident γ rays at 202, 364, 476, 550, and 574 keV with a half-life of 7.0 ± 0.5 μs correlated with the implantation of the selected $A/Q=140/27=5.185$ recoils. The γ spectra, single and double gated, are shown in Fig. 2. None of those transitions have been observed so far in the isomeric or radioactive decays in known mass $A=140$ nuclei. The same holds for the isobars of mass $A=145$ representing $A/Q=145/28=5.179$ charge state ambiguity for $A=140$ recoils. All five γ lines are in coincidence with each other which places them in one cascade.

TABLE I. ^{140}Dy $I^{\pi}=(8^{-})$ isomer decay: γ-ray energies and intensities established from coincidence data. The total transition intensity I_{TOT} includes internal conversion coefficient α_{TOT} for given multipolarity $E\lambda$.

E_γ (keV)	I_γ (arb.u.)	$E\lambda$	α_{TOT} [a]	I_{TOT} (arb.u.)
202.2(2)	81(3)	$E2$	0.231	100(3)
364.0(2)	99(4)	$E2$	0.037	103(4)
476.1(2)	96(4)	$E2$	0.017	98(4)
550.0(2)	100(4)	$E2$	0.012	101(4)
573.8(2)	103(5)	$E1$	0.004	103(5)

[a]Calculated using HSICC code at http://www.nndc.bnl.gov

An analysis of triple coincidences restricted to $\gamma\gamma\gamma$ events occurring within a 4 to 50 μs window after the MCP recoil signal was also performed. Two lines at 45.8 and 52 keV corresponding to dysprosium K_α and K_β X rays were revealed after setting double gates on five new transitions, see Fig. 2(c). Thus we attribute the cascade to the decay of a new isomeric state in ^{140}Dy.

The spectrum of time differences between the MCP signals and five γ transitions (double gated) is presented in Fig. 2(d). It displays the decay pattern of the isomer fitted with a half-life of 7.0 ± 0.5 μs. The half-lives of the individual transitions are all consistent with 7 μs, within the statistical errors.

The sequence of the γ lines in the cascade cannot be determined by coincidence analysis. However, the intensities and energies of the transitions can be arranged to resemble a rotational band in a deformed nucleus fed by the isomeric level; see Table I and Fig. 3. Also, a comparison to the decay patterns of $I^{\pi}=8^{-}$ K isomers in the less exotic $N=74$ even isotones of ^{134}Nd, ^{136}Sm, and ^{138}Gd shows striking similarity as displayed in Fig. 3. This leads us to the interpretation of the isomeric level at 2166 keV as an $I^{\pi}=(8^{-})\{\nu9/2^{-}[514]\otimes\nu7/2^{+}[404]\}$ K isomer decaying via the $8^{+}\rightarrow6^{+}\rightarrow4^{+}\rightarrow2^{+}\rightarrow0^{+}$ cascade belonging to the ground-state band in ^{140}Dy. The energy of 2150 keV predicted in [14] for this two-quasineutron configuration is very close to the observed value of 2166 keV, closer than for less exotic $N=74$ K isomers of the same structure [12,14].

Considering the 574 and 550 keV transitions as the candidates for the $E1$ isomeric transition from the $I^{\pi}=8^{-}$ ($K=8$) to the $I^{\pi}=8^{+}$ ($K=0$) level we find Weisskopf hindrance factors F_W of $5.3(4)\times10^9$ and $4.7(3)\times10^9$, respectively. This is very close to the values $8.4(6)\times10^9$, $5.9(4)\times10^9$, and $4.7(8)\times10^9$, reported for 8^{-} K isomers in neighboring $N=74$ isotones of ^{134}Nd, ^{136}Sm, and ^{138}Gd [12]. Corresponding hindrance per degree of K-forbiddenness f_ν, where $F_W=f_\nu^{(\Delta K-\lambda)}=f_\nu^7$, amounts to 24.5(3) and 24.1(3) for 574 and 550 keV transitions, respectively. We cannot unambiguously conclude on the ordering of the 574 and 550 keV transitions based on these small differences. However, the proposed level scheme based on systematic energy trends seems to be most likely (see Fig. 3).

The calculated yield for ^{140}Dy production in this reaction is about 30 μb [23], i.e., 6×10^{-5} of the 500 mb fusion-evaporation cross section. This is in good agreement with the experimental cross section of 20 μb, which includes an estimated 3% RMS transmission and a 100% efficiency of the recoil-γ correlations within the μs time scale.

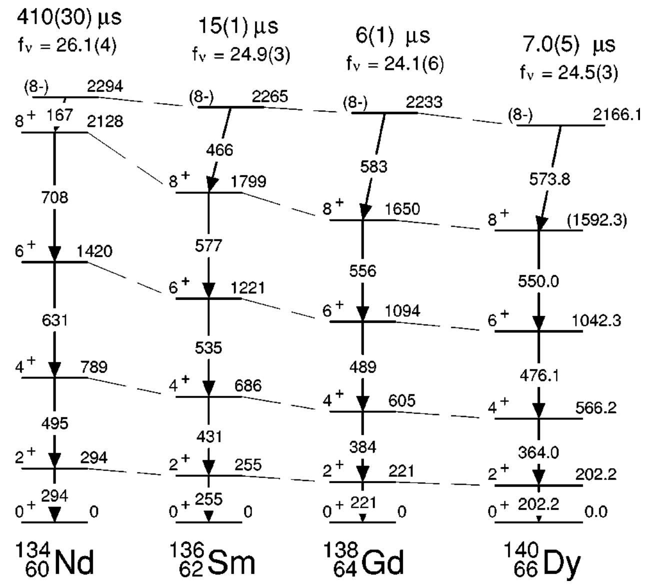

FIG. 3. Level scheme of ^{140}Dy proposed in this work and the systematics of the decay properties of $I^{\pi}=8^{-}$ K isomers in $Z\geqslant60$, $N=74$ isotones. The f_ν values derived from the displayed decay schemes are also listed.

The position of the 2^{+} level in ^{140}Dy influences the fine structure branching ratio $I_p(2^{+})$ for the proton emission from ^{141}Ho [6]. The observed 2^{+} energy of 202 keV is in agreement with the lower limit of 190 keV reported in [11]. It is higher than the 160 ± 20 keV, predicted within the framework of particle-hole N_pN_n symmetry [24]. It differs from $E(2^{+})=138$ keV for ^{156}Dy, which could be considered as the "$N=82$ mirror" of ^{140}Dy, within the N_pN_n scheme. Following Grodzins's formula [25,26] the observed value $E(2^{+})=202$ keV gives a deformation parameter β_2 of 0.244 for ^{140}Dy. This is a somewhat smaller quadrupole deformation than the previously anticipated values of, e.g., $\beta_2=0.267$, $\beta_4=-0.05$ listed in [27], $\beta_2=0.275$ obtained in [14], or $\beta_2=0.27$, $\beta_4=-0.06$ used for the interpretation of observed proton decay rates from ^{141}Ho [10]. However, the value of $\beta_2=0.244$ is close to the $\beta_2=0.25$ derived from observed level schemes of $^{141g.s.,m}$Ho [11]. These results are consistent with the commonly used assumption [6–9], that there is no shape change during the proton emission process.

The experimental data on the level schemes of ^{140}Dy (this work) and ^{141}Ho [9–11] provide reliable experimental input for the predictions of proton emission rates. Following the non adiabatic coupled-channel model [6,7] we calculate the $I_p(2^{+})$ for the proton emission from the $7/2^{-}[523]$ ground state and $1/2^{+}[411]$ isomer in ^{141}Ho. As discussed in [6,7] the $I_p(2^{+})$ depends weakly on the β_2 values. In Fig. 4 the branching ratios are plotted as a function of β_4 with β_2 fixed as 0.244. For the expected hexadecapole deformation value of $\beta_4\approx-0.05$ one gets $I_p(2^{+})$ close to 2% for the $7/2^{-}[523]$ ground state. It is three times lower than the pre-

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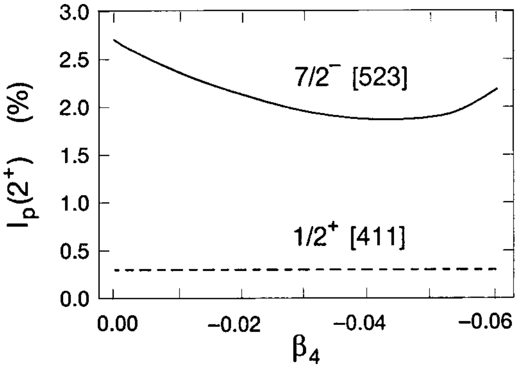

FIG. 4. Proton branching ratio $I_p(2^+)$ to the 2^+ level in ^{140}Dy in the proton decay of ^{141}Ho calculated as a function of β_4 deformation with a fixed value of $\beta_2=0.244$ for two deformed resonances: the $7/2^-[523]$ ($^{141\text{g.s.}}$Ho; solid line) and $1/2^+[411]$ (^{141m}Ho; dashed line).

viously reported $I_p(2^+)=6\%$ [6] based on phenomenologically estimated 2^+ state energy of 160 keV [24] in ^{140}Dy. The $I_p(2^+)$ for the $1/2^+[411]$ state decay does not show the variation within the considered range of β_4 and stays at a low value of 0.3%.

The $I_p(2^+)$ value of about 2% is above the reported experimental upper limit of 1% [11]. The present RMS based setup for proton radioactivity studies at the HRIBF [2,17] has a detection sensitivity of $I_p(2^+)\approx 0.5\%$ for the 4 ms activity of $^{141\text{g.s.}}$Ho produced in the fusion-evaporation reaction with 300 MeV ^{54}Fe projectiles and a ^{92}Mo target. Therefore, a measurement verifying the calculated and reported $I_p(2^+)$ values for $^{141\text{g.s.}}$Ho is within our sensitivity limits. However, the search for the fine structure in the 6 μs decay of ^{141m}Ho requires further enhancements to the digital electronics capabilities, in particular an extension of the present 10 μs "proton catcher" observation window [2,3,21].

In summary, a new 7 μs γ cascade identified at the RMS is interpreted as the γ transitions following the decay of the first K isomer observed in the daughter of a proton unbound nucleus, the $I^\pi=8^-$ $(K=8)$ $\{\nu 9/2^-[514]\otimes\nu 7/2^+[404]\}$ state in ^{140}Dy. The observed energy of 2166 keV is in excellent agreement with the predicted value of 2150 keV [14]. The hindrance per degree of K-forbiddenness, i.e., f_ν value, ranging from 26 to 24 for these K isomers in $Z\geqslant 60$, $N=74$ isotones including ^{140m}Dy, is quite constant, indicating the robustness of the underlying two-quasineutron configuration. Interestingly, the observed $E(2^+)$ energy of 202 keV in ^{140}Dy is significantly higher than the 138 keV known in the "$N=82$ mirror" nucleus ^{156}Dy.

The branching ratio for the proton emission from ground and isomeric states in ^{141}Ho is calculated taking the experimental level scheme of ^{140}Dy ground-state band as an input. The predicted branching ratio $I_p(2^+)\approx 2\%$ for $^{141\text{g.s.}}$Ho and the precisely known energy of a possible fine structure transition are essential for the study of the proton radioactivity of $^{141\text{g.s.}}$Ho.

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