Proton Decay of an Intruder State in ^{185}Bi

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The new proton radioactivity ^{185m}Bi has been observed, produced *via* the ^{95}Mo(^{92}Mo, pn)^{185}Bi reaction. Its decay proceeds from the low-lying $\frac{1}{2}^+$ intruder state in ^{185}Bi to the ^{184}Pb ground state with the emission of a proton of energy 1.585 ± 0.009 MeV and a half-life of 44 ± 16 μs. This marks the first observation of proton radioactivity above the $Z = 82$ closed shell, and it has been used to obtain the admixture of a 0^+ intruder state in ^{184}Pb into the ^{184}Pb ground-state wave function.

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The proton drip line represents one of the fundamental limits to nuclear existence. Nuclei lying beyond this point are energetically unstable to the emission of a proton. Proton decay is an inherently simple process, since the proton can be considered to be preformed inside the decaying nucleus. This simplicity can be exploited to obtain unique spectroscopic information beyond the proton drip line. In particular, the proton decay transition rates are extremely sensitive to the energy and orbital angular momentum of the proton, while being relatively insensitive to the details of the nuclear potential. Although the proton drip line has been extensively mapped out for $Z < 50$, no examples of ground-state proton radioactivity have been observed in this region. This can be attributed to the relatively low Coulomb barriers in light nuclei, which can result in proton-unbound nuclei being too short lived ($t_{1/2} < 1$ μs) to be observed experimentally. For $Z > 50$ two regions of proton radioactivity have been discovered, one near the $N = 82$ shell closure [1–5], the other just above $Z = 50$ [6–9]. The region near $N = 82$ is predicted [10] to be approximately spherical, and proton decay rates have been well reproduced by W. K. B. calculations [1] assuming simple spherical shell model states and spectroscopic factors of unity. These studies have revealed surprising shell reversals in the ground-state configurations [2], and in some cases the shell separations have been directly determined from isomeric decays [1,3,5]. For the proton transitions around $Z = 53-55$, large hindrance factors are required (e.g., ~ 30 for ^{113}Cs [7,8]) that have been attributed [7,11] to the onset of a predicted region of deformation [10]. By exploring new regions of proton radioactivity we would expect to obtain further unique information on nuclear level structures. Here we report the discovery of a new region of proton radioactivity in which proton decay from an intruder state is observed for the first time.

In this Letter, results on proton radioactivity from ^{185}Bi, by far the heaviest proton emitter found to date, are presented. ^{185}Bi has a single proton outside the $Z = 82$ closed shell. The existence of low-lying intruder states in the neutron-deficient odd-Z nuclei in this region is expected to play a significant role in the decays for these emitters. In the odd-A Bi isotopes, the $1/2^+$ intruder state, with proton configuration $\pi(h_{9/2})^2\,(s_{1/2})^{-1}$, appears as a low-lying isomeric state above the $9/2^-$ ground state [12]. For the even-A Pb daughter nuclei, low-lying 0^+ intruder states having the configuration $\pi(h_{9/2})^2\,(s_{1/2})^{-2}$ have been observed [13].

In contrast to the other regions of the proton drip line, where the $1p2n$ and $1p3n$ fusion-evaporation channels have been used to study proton radioactivity, fission competition is the major obstacle. Hence we chose to produce ^{185}Bi via the $1p1n$ evaporation channel, using a relatively cold compound nucleus reaction $^{92}\mathrm{Mo} + {}^{95}\mathrm{Mo} \rightarrow {}^{187}\mathrm{Po}$ at excitation energies between 25 and 30 MeV. A 410 MeV, 2 particle nA ^{92}Mo beam from the ATLAS accelerator at Argonne National Laboratory was used to bombard a 500 μg/cm^2 isotopically enriched target of ^{95}Mo for a period of 40 h. Reaction products entered the fragment mass analyzer (FMA) [14], where they were separated from the primary beam on a microsecond time scale and dispersed in M/q (mass/charge) at the focal plane. A thin position-sensitive multiwire proportional counter (MWPC) at this location provided M/q, time of arrival, and energy loss signals. After passing through this detector, the ions traveled 40 cm farther and were implanted

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approximately 10 μm deep into a double-sided silicon strip detector (DSSD) of thickness 65 μm, area 16×16 mm^2, and having 48 orthogonal strips on the front and rear, respectively [15]. Events in the DSSD were time stamped and identified as either an implant or decay particle, depending on whether they were in coincidence or anticoincidence with a signal from the MWPC. Reaction recoils were separated from scattered beam events in the DSSD by their energy and time of flight from the MWPC. The ion optics of the FMA allowed three charge states of the same mass to be implanted into the DSSD, with essentially uniform illumination.

With this arrangement the 2304 individual *x,y* quasipixel locations in the DSSD served as memory cells, allowing the observation of the time and position correlations between the implantation of an individual ion and its subsequent decay products. In this region of the chart of the nuclides, proton emission must compete with alpha decay, with the decaying states having half-lives in the 0.1–200 ms range. The capability of time and position correlating the proton with the alpha decay of the daughter nucleus makes possible the clean identification of even extremely weak proton decay channels.

The decay events in this experiment occurred in two time regions. A cluster of 14 events all decayed within 200 μs of the implantation event, while the remaining events all had decay times longer than 3 ms. Figure 1(a) shows the energy spectrum of all decay events in the DSSD. The spectrum is dominated by known alpha decay peaks ($\sim$25 keV FWHM) mainly from ^{185}Pb, and an alpha escape bump around 1.5–2 MeV. Figure 1(b) shows the energy spectrum of decay events following the implantation of mass 185 recoils. Figure 1(c) shows the energy spectrum of decay events occurring within 200 μs of the implantation event. All of these events have $A = 185$ parents. A peak is present at an energy of 1.585 ± 0.009 MeV, calibrated using the known ground-state decay protons from ^{147}Tm [1], which is found to be correlated with known alphas from ^{184}Pb [16]. On this basis the peak is assigned to the proton decay of ^{185}Bi, with a corresponding Q value of 1.594 ± 0.009 MeV, and an associated cross section of $\sim$100 nb using an efficiency for the FMA of 20%.

The measured half-life of 44 ± 16 μs is compared in Table I with WKB barrier transmissions calculated as described by Hofmann [1], using two different sets of optical model parameters [17,18]. The results are given for ℓ values of 0 and 5, corresponding to the proton orbitals $s_{1/2}$ and $h_{9/2}$. From Table I, it is seen that proton emission from the likely $h_{9/2}$ ground state of ^{185}Bi can be ruled out, since the observed transition is much faster than predicted. We therefore interpret the observed proton group as originating from the metastable $s_{1/2}$ intruder state in ^{185}Bi. What remains is to identify which state in the daughter nucleus ^{184}Pb is populated by the proton decay.

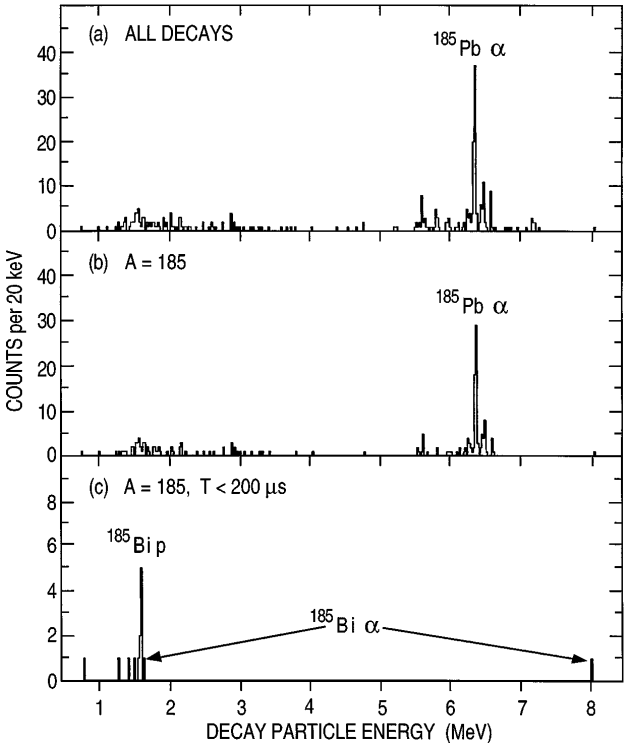

FIG. 1. (a) Energy spectrum of all decay events in the DSSD. The peaks above $\sim$5 MeV represent alpha decays, and the broad structure extending down to $\sim$1.4 MeV is due to alphas emitted in the backward direction, which deposit only part of their energy before escaping from the DSSD. (b) Energy spectrum of decay events from $A = 185$ implants. (c) Energy spectrum of decay events which occurred within 200 μs of the implantation event.

A simple parabolic extrapolation of the energies of the 0^+ intruder states in neutron-deficient Pb isotopes [13] gives an estimated value of 0.60 MeV for the excitation energy of the 0^+ intruder in ^{184}Pb. This reduction in available decay energy translates to a proton decay rate at least 7 orders of magnitude slower than the rate to the ^{184}Pb ground state. Thus the ground-state transition will dominate, despite being hindered by configuration effects. This argument would remain valid for other possible excited state configurations, such as a low-lying prolate band structure recently observed in ^{186,188}Pb [19]. We conclude that the observed ^{185m}Bi proton decay proceeds to the ^{184}Pb ground state. Figure 2 shows the proposed ^{185m}Bi decay scheme, including the predominant proton configurations suggested for the various states. Estimated excitation energies in MeV obtained by parabolic extrapolation from known isotopes [12,13] are given in square brackets for the relevant states shown.

Proton decay between ^{185m}Bi and the ^{184}Pb ground state is expected to be inhibited because it involves a complex particle rearrangement. However, the decay can take place through a small 2p-2h (two-particle–two-hole) admixture in the ^{184}Pb ground-state wave function, and

TABLE I. ^{185m}Bi proton partial half-lives (μs).

Energy (MeV)	Measured $t_{1/2,p}$	Calculated $t_{1/2,p}$ [a] BG [b]	Perey [c]	Proton orbital
1.585 ± 0.009	44 ± 16	2.2	1.4	$s_{1/2}$
		29 000	15 000	$h_{9/2}$

[a] Calculated proton partial half-life, assuming a spectroscopic factor of unity.
[b] Using Becchetti-Greenlees optical potential [17].
[c] Using Perey optical potential [18].

should provide a clean way to measure the mixing intensity. A simple model [20] for the ^{184}Pb ground-state wave function gives

$$|0^+_{\text{gs}}\rangle = a|0\text{p-}0\text{h}\rangle + b|2\text{p-}2\text{h}\rangle, \quad \text{where } |a|^2 + |b|^2 = 1\,.$$

Such 2p-2h admixtures have been studied for neutron-deficient Pb isotopes, giving mixing intensities $|b|^2$ of 0.003 for ^{194}Pb [20], 0.005 for ^{192}Pb [20], >0.02 for ^{190}Pb [20], and <0.09 for ^{186,188}Pb [21]. For the present case we assume that the ^{185m}Bi proton decay proceeds from the essentially pure 2p-1h state to the admixed 2p-2h component in the ^{184}Pb ground state. Using the experimental and calculated proton partial half-lives given in Table I, we obtain $0.03 \leq |b|^2 \leq 0.07$ for the mixing intensity of the $\pi(h_{9/2})^2(s_{1/2})^{-2}$ 2p-2h state in the ^{184}Pb ground state, using the Becchetti-Greenlees optical potential [17]. The corresponding limits for the Perey potential [18] are $0.02 \leq |b|^2 \leq 0.04$. These values are consistent with the results quoted above for $^{186-194}$Pb and provide an anchoring data point for the theoretical exploration of shape coexistence in these highly neutron-deficient nuclei.

Because the excitation energy of ^{185m}Pb is not known, it is not possible to compare the measured proton Q value directly with mass predictions. A simple parabolic extrapolation based on the excitation energies for the $1/2^+$ intruder states in ^{195}Bi, ^{193}Bi, ^{191}Bi [22], and recent results for ^{189}Bi [23,24] gives an estimated excitation energy of 0.22 MeV for the energy of this state in ^{185}Bi. This corresponds to a ground-state proton Q value of 1.37 MeV. Predicted values are 1.57 [25], 1.58 [26], and 2.02 MeV [10]. The Liran-Zeldes mass formula [25] is known to reproduce ground-state alpha-decay Q-value systematics very well. In this case the prediction for ^{185}Bi is 7.96 MeV, which would give a value of 8.18 MeV for the isomeric state assuming an excitation energy of 0.22 MeV. One lone event is present in Fig. 1(c) with an alpha Q value of 8.21 MeV. It is correlated with an escape alpha having a decay time of 3.9 s, consistent with being from the ~20% alpha branch of 3.4 s ^{181}Tl [27]. A further single uncorrelated event is observed in the alpha-escape region at an energy of 1.68 MeV, significantly above the proton peak. We tentatively assign these two events to an alpha branch of ~15% from the same ^{185m}Bi state as the proton decay (this assumption would not significantly alter any of the previous discussions on the proton decay branch). The implied partial half-life of the ^{185m}Bi alpha decay is 310 ± 230 μs, resulting in an alpha-decay reduced width δ^2 of 7.2 ± 5.3 keV, using the formalism of Rasmussen [28]. This transition can be compared with the alpha decay of the neighboring even-even nucleus ^{184}Pb, for which $\delta^2 = 49$ keV. We obtain a reduced hindrance factor (HF), defined [28] as the ratio of the alpha reduced widths, of $1.8 \leq \text{HF} \leq 12$. This compares well with values obtained for the $1/2^+ \rightarrow 1/2^+$ alpha transitions from heavier odd-*A* Bi isotopes [22]. On this basis, we tentatively interpret the observed alpha decay as the transition between ^{185m}Bi and the $1/2^+$ ground state of ^{181}Tl, which is illustrated in Fig. 2.

The ground state of ^{185}Bi should decay predominantly by an unhindered alpha decay to the $9/2^-$ state in

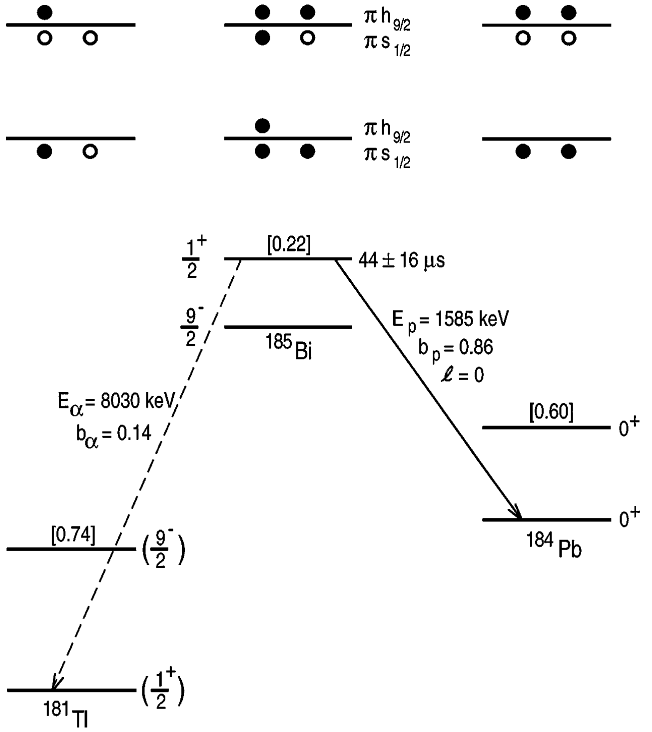

FIG. 2. Proposed decay scheme of ^{185m}Bi. Suggested proton configurations for each of the six states are given. The numbers in square brackets are estimated excitation energies in MeV.

^{181}Tl. Systematics would indicate an alpha-decay energy $\sim$7.1 MeV with a half-life $>$10 ms. As can be seen from Fig. 1(b), which shows all decays associated with $A = 185$ isobars, no events are present in this energy region. This represents an upper limit on the production cross section for the production of ^{185}Bi in its ground state of $\sim$10 nb. In previous studies of neutron-deficient Bi isotopes (e.g., [29]) using different reactants and compound-nucleus excitation energies, the $9/2^-$ ground state has been more strongly populated than the $1/2^+$ intruder state. One possible explanation would be that the combination of a relatively low compound-nucleus excitation energy and a high degree of fission competition ($>$99%) may favor the production of lower spin states associated with central collisions. Future experiments are planned for this region that will further explore this interesting observation.

In conclusion, decays from the heaviest known proton emitter ^{185}Bi have been characterized as coming from an $s_{1/2}$ intruder configuration. This marks the first observation of proton radioactivity above the $Z = 82$ closed shell. The decay proceeds to the ground state of ^{184}Pb through a 2p-2h admixture in the final state. These new results indicate the unique importance of proton radioactivity in providing detailed spectroscopic information beyond the proton drip line.

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