Proton and α radioactivity of ^{185}Bi

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Proton and α emission from ^{185}Bi have been confirmed and measured with improved statistics. The ^{185}Bi nuclei were produced via the ^{95}Mo(^{92}Mo,pn) reaction at a bombarding energy of 420 MeV. The proton decay energy from the $1/2^+$ intruder state in ^{185}Bi to the ^{184}Pb ground state was measured to be 1.598(16) MeV with a proton branching ratio $b_p=0.85(6)$. An α decay branch from the same state was measured, $b_\alpha=0.15(6)$, with an energy of 8.08(3) MeV. The state has a half-life of 50(8) μs. In addition, the α branching ratio of the ground state of ^{184}Pb was determined for the first time to be $b_\alpha=0.23(14)$.

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Neutron deficient odd-A Bi isotopes are characterized by a $\pi(h_{9/2})^1$ ground state and a moderately oblate $\pi(h_{9/2})^2(s_{1/2})^{-1}$ intruder state [1]. These states were most recently observed in a study of α decays from ^{187}Bi [2]. In ^{185}Bi a weakly produced proton decay peak was assigned to a low-lying $1/2^+$ intruder state, but no evidence was found for the expected ground-state α decay [3]. The proton decay had a low spectroscopic factor implying large configuration hindrance between intruder and normal states in the mother and daughter nuclei. This in turn implied a shape change associated with the proton decay. Such a mechanism is presently unique to ^{185}Bi and is beyond the current scope of theoretical models of proton decay which assume an inert core. One short-lived decay event with an energy of 8.03 MeV was observed and tentatively assigned to an α decay from the $1/2^+$ state in ^{185}Bi to the $1/2^+$ ground state in ^{181}Tl. The present paper describes a new study of the decay of ^{185}Bi with improved statistics.

A 4.5 pnA beam of 420 MeV ^{92}Mo ions from the ATLAS accelerator was used to bombard a 811 μg/cm^2 isotopically enriched target of ^{95}Mo for 85 h. The ^{185}Bi nuclei were produced via the $1p1n$ evaporation channel from the relatively cold compound nucleus ^{187}Po* at excitation energies between 23 and 34 MeV. The reaction products were separated according to their mass/charge (M/q) ratio by using the Argonne Fragment Mass Analyzer (FMA) [4] and subsequently implanted into a 60 μm thick double-sided silicon strip detector (DSSD) of area 40×40 mm^2 and having 40 strips on the front side orthogonal to 40 strips on the back. The FMA was set to focus $M/q=185/34$ ions at the center of the focal plane, with $q=33$ and 35 ions also being accepted. The mass information of the recoiling ions (M/q) was given by a parallel grid avalanche counter (PGAC) positioned at the focal plane. Implantation and decay events in the DSSD, identified by the coincidence and anticoincidence of DSSD-PGAC signals respectively, were time-stamped by a 1 MHz clock. A 3.6 mg/cm^2 Ni degrader foil was placed in front of the DSSD, reducing the implantation energy to ≈30 MeV in order to avoid excessive overloading of the amplifiers. The experiment was sensitive to decays occurring at least 6 μs after recoil implantation.

Figure 1(a) shows the energy spectrum of decay events following an implant event in the same pixel within 5 s. One observes the known ^{184}Pb and ^{185}Pb α peaks arising from the stronger reaction channels. Figure 1(b) shows the same decay spectrum with the additional condition that the decays were preceded by a mass 185 implant. ^{184}Pb α decays in this spectrum are produced as a daughter product of the proton decay from ^{185}Bi. The ground state of ^{185}Bi is expected to have a strong α-decay branch to an $h_{9/2}$ intruder state in ^{181}Tl with an α energy $\sim$7.0–7.5 MeV and a half-life $\sim$10–100 ms. However, there is no evidence in Fig. 1(b) for a single event in this energy region corresponding to an upper cross-section limit $\sim$2 nb.

Figure 1(c) shows the decay events following a mass 185 recoil within 300 μs. A time-dependent energy correction has been applied to these data (due to the amplifier recovery response immediately following implantation), the largest correction being ≈20 keV. The peak at an energy of 1.618(11) MeV is found to be correlated with the known α decay of ^{184}Pb [5,6], confirming the previous result of proton emission from ^{185}Bi [3]. The energy value was obtained using as a reference the known proton peak at 1.051(3) MeV from the ^{147}Tm ground state [7] and should be compared with the previous result of 1.585(9) keV. This gives a weighted mean value for both experiments of 1.598(16) MeV, where the uncertainty is the variance of the two measurements. The cluster of five events at 8.08(3) MeV is assigned to an α branch from the $1/2^+$ state in ^{185}Bi to the $1/2^+$ ground state in ^{181}Tl that was previously assigned on the basis of only one 8.03 MeV event [3].

The half-lives of the proton and α decay lines agree within errors and we assign them to separate decay branches of the $1/2^+$ state of ^{185}Bi [$b_p=0.85(6)$ and $b_\alpha=0.15(6)$] with a combined half-life of 50(8) μs. We assume a negligible β^+ + electron capture branch. This is a more precise

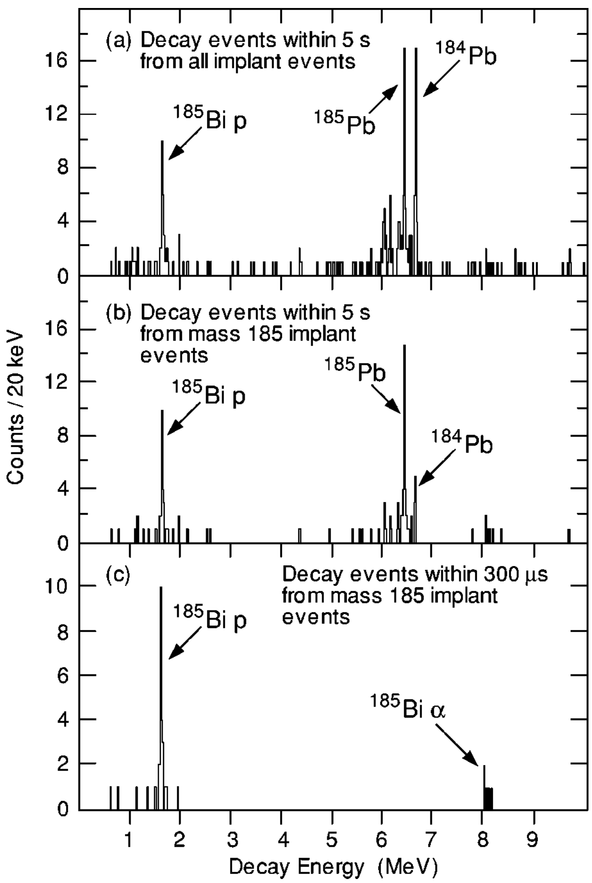

FIG. 1. (a) Energy spectrum of all decay events detected in the DSSD occurring within 5 s after a recoil implantation produced in the ^{92}Mo+^{95}Mo reaction. (b) Same as (a) except requiring a mass = 185 implant. (c) A more stringent time condition on the decay time interval ($<$300 μs) clearly reveals proton and α decay branches from the 1/2$^+$ state of ^{185}Bi.

estimate of the half-life and is compatible with the previous result of 44(14) μs [3]. This gives a weighted mean value of 49(7) μs. The cross section for the production of the 1/2$^+$ state is $\approx$60 nb.

The correlation of the proton decay of ^{185}Bi with the 6.63 MeV α decay of ^{184}Pb allowed the first determination of the ground state α branching ratio of ^{184}Pb=0.23(14). The 480(25) ms half-life [6] leads then to a partial half-life for α decay of 2.1$\pm$1.3 s corresponding to a reduced width of δ^2 =13(8) keV using the Rasmussen formalism [8].

The proton partial half-life of 58(8) μs compares with a calculated value of 2.4(5) μs assuming unhindered $s_{1/2}$ proton decay through a Becchetti-Greenlees optical potential [9] (see Table I). This implies an experimental proton decay spectroscopic factor of 0.04(1), confirming significant hindrance between the 1/2$^+$ intruder state in ^{185}Bi and the ground-state of ^{184}Pb. It is interesting to note that a similar spectroscopic factor of 0.034 is found immediately below the Z=82 shell closure for proton decay from an excited $h_{11/2}$ single hole state in ^{177}Tl to the ground state of ^{176}Hg [10]. In the present case admixing of the spherical ^{184}Pb ground-state configuration may occur with low lying 0$^+$ oblate and prolate deformed structures corresponding to 2p2h and 4p4h configurations. Cocks *et al.* [11] have reported in-beam gamma-ray measurements showing the strong feeding of a highly deformed prolate band structure in ^{184}Pb from which they are able to infer the existence of a 0$^+$ bandhead at an excitation energy around 610 keV. Even more recently Andreyev *et al.* [12] have reported the existence of a 0$^+$ intruder state at 577(40) keV fed from the alpha decay of ^{188}Po. This may represent the same prolate deformed structure as Cocks *et al.* inferred, however, it is also possible that this state is associated with an oblate structure. The neighboring isotope ^{186}Pb has been shown to have 0$^+$ configurations for the three lowest energy quantum states corresponding to spherical, oblate and prolate structures [13]. The admixing of these states will influence the proton decay rate from the 1/2$^+$ intruder state in ^{185}Bi.

TABLE I. Comparison of the partial proton half-life of the ^{185}Bi proton radioactivity with theoretical calculations for the $s_{1/2}$ and $h_{9/2}$ shell model orbitals. The experimental spectroscopic factor S_{lj}^{expt} has been calculated for the appropriate orbital.

E_p(MeV)	B_p	$T_{1/2,p}^{\mathrm{expt}}$	Proton orbital	$T_{1/2,p}^{\mathrm{theor}}$	S_{lj}^{expt}
1.598(16)	0.85(6)	58(8) μs	$s_{1/2}$	2.4(5) μs	0.04(1)
			$h_{9/2}$	15.5(35) ms	

1/2$^+$ 2p1h states in odd-A Bi isotopes and 2p2h states in even Pb isotopes show a very similar parabolic energy dependence on neutron number [2]. Batchelder *et al.* have demonstrated that the excitation energy of the 2p1h 1/2$^+$ intruder state is still decreasing at ^{187}Bi [112(21) keV] corresponding to the neutron mid-shell value of N = 104 [2]. The absence of any decays from the 9/2$^-$ state precludes establishing a value for this energy in ^{185}Bi. However, the energy of the intruder-state α decay is broadly consistent with the energy expected based on the corresponding transitions in ^{187,189}Bi [2,14] where ^{189}Bi has an intruder excitation energy of 190(40) keV. This suggests that the excitation energy of the 1/2$^+$ state in ^{185}Bi remains low, although the minimum may already have been reached for ^{187}Bi (mid-shell). The partial half-life of the α transition is 330(140) μs, corresponding to an α reduced width of δ^2=7(3) keV which is rather low compared to the value of 31(10) keV obtained for the equivalent transition from ^{187}Bi [2].

The absence of any evidence for α decays from the 9/2$^-$ state is particularly surprising since it is fed seven times more strongly than the 1/2$^+$ intruder state in the analogous ^{97}Mo+^{92}Mo fusion reaction used to produce ^{187}Bi [2]. Another interesting comparative feature is that in absolute terms the intruder state in ^{185}Bi appears to be produced more strongly than in ^{187}Bi lying closer to stability. This suggests that most of the gamma-cascade intensity is feeding through the 1/2$^+$ state rather than being largely bypassed as occurs in more stable odd-A Bi isotopes. Alternatively, the 1/2$^+$ state may lie well below the spherical $h_{9/2}$ orbital, and may in fact be the ground state. Establishing the mechanism for the preferential feeding of the 1/2$^+$ intruder in ^{185}Bi will require in-beam gamma and conversion electron studies at the extreme limit of experimental sensitivities.

In summary, the decay of an intruder state in ^{185}Bi by proton and α branches has been confirmed and measured with improved precision. It represents the one clear example of a shape-changing proton transition in proton radioactivity studies. Such transitions represent a new challenge to extend theories of proton emission.

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