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Author
Wilmarth, P.A.

Publication Date
1986-09-01

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

Submitted to Zeitschrift für Physik A

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P.A. Wilmarth, J.M. Nitschke, R.B. Firestone, and J. Gilat

September 1986

NUCLEAR SCIENCE DIVISION

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

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P. A. Wilmarth, J. M. Nitschke, and R. B. Firestone
Nuclear Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720 USA

J. Gilat
Soreq Nuclear Research Center
Yavne 70600, Israel
and
Nuclear Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720 USA

This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

Abstract:
Several new β–delayed proton precursors were produced in (HI; xn, yp) reactions at the LBL SuperHILAC and studied with the isotope separator OASIS. Unambiguous Z-identifications were obtained in all cases by observing characteristic x-rays coincident with the protons. Ground state spins were determined in favorable cases. The lowest 2^+ levels in the rotational bands of ^{126}Ce and ^{130}Nd were confirmed.

Our on-going study [1-4] of the decay properties of very neutron-deficient lanthanides has resulted in the identification of several new β-delayed proton emitters. These new isotopes were produced *via* (HI; xn, yp) reactions at the SuperHILAC's on-line isotope separator OASIS and decay studies were carried out in a low background spectroscopy laboratory [1]. The mass numbers were uniquely determined by calibrating the isotope separator with stable rare earth mass markers introduced into the surface ionization source. The isotope of interest was selected by an analyzing slit in the focal plane of the mass separator, transported ionoptically to a fast cycling tape and periodically positioned between an array of detectors which recorded all possible decay modes on an event–by–event basis. Z-identifications were obtained by observing characteristic x-rays in coincidence with the β-delayed protons. Two general classes of decays were of interest: (1) direct or β-delayed particle emission along with any coincident γ-rays, x-rays, or positrons, and (2) γ-rays in coincidence with positrons or x-rays from electron capture and conversion processes. The results are discussed below by mass number and summarized in Table 1.

A=124: A β-delayed proton activity with a half-life of 1.2 ± 0.2 s was assigned to the new isotope ^{124}Pr on the basis of the Ce K x-rays observed in coincidence with the protons. La K x-rays and γ-rays of 70, 113 and 166 keV were also observed in coincidence with the protons but the gamma transitions cannot be uniquely placed since the level scheme of ^{123}La is not known. Assuming any combination of M1 or E2 multipolarities for the above gamma transitions, all La K x-rays can be accounted for by internal conversion. The possibility that the La K x-rays could originate from a weak β-delayed proton branch in ^{124}Ce can be excluded for the following reasons: (1) internal conversion can account for all La K x-rays, (2) statistical model calculations indicate that the proton branching ratio for ^{124}Ce should be about 10^3 times weaker than for ^{124}Pr, and (3) the decay of the proton activity gives, within the statistical uncertainty, no indication of a second, longer lived activity.

A weak 142 keV γ-ray decaying with a ~1 s half-life is tentatively assigned to ^{124}Pr β-decay and could be the 2^+ to 0^+ transition in ^{124}Ce.

A=125: We previously reported the identification of a β-delayed proton branch in ^{125}Ce [2] without coincident photon data to unambiguously determine the Z of the precursor. In a more recent experiment, a β-delayed proton activity observed with a half-life of 10 ± 1 s in coincidence with La K x-rays confirmed the previous Z assignment. A comparison of the intensities of the 230 keV (2^+ to 0^+), 421 keV (4^+ to 2^+), and 575 keV (6^+ to 4^+) transitions in ^{124}Ba with statistical model calculations indicates a spin of 5/2 for ^{125}Ce. This is in contradiction to Nilsson model predictions of a spin $1/2^+$ assuming a ground state deformation of $\varepsilon_2 = 0.27$.

A=127: A β-delayed proton activity with a half-life of 1.5 ± 0.3 s was assigned to ^{127}Nd on the basis of coincident Pr K x-rays confirming the previous Z assignment [2]. A γ-ray of 170 KeV was measured in coincidence with protons and is attributed to the 2^+ to 0^+ transition in ^{126}Ce [6].

A=131: A 1.2 ± 0.2 s β-delayed proton activity coincident with Pm K x-rays identified the new isotope ^{131}Sm. Delayed protons from 25 ± 4 s ^{131}Nd, previously reported in ref. 5, were also detected. In a cross bombardment of ^{40}Ca on ^{94}Mo, eliminating Sm production, only ^{131}Nd protons were seen confirming the Z assignment of the new Sm proton precursor. Intense γ-rays of 159 and 254 KeV observed in coincidence with protons arise from the 2^+ to 0^+ transitions in ^{130}Nd and ^{130}Ce respectively. This observation confirmed the 2^+ level assignment for ^{130}Nd from ref. 6 and agrees with the systematics for Nd isotopes [4]. A comparison of the final state feedings in ^{130}Ce with statistical model calculations imply a spin of 5/2 for ^{131}Nd. A similar analysis for ^{131}Sm cannot be completed at this time.

A=140: Delayed protons with a half-life of 2.4 ± 0.5 s are associated with the new isotope ^{140}Tb based on coincident Gd K x-rays. The decay of the 329 keV (2^+ to 0^+) γ-ray following β-decay of ^{140}Tb yielded a half-life of 2.3 ± 0.6 s. This is the first unambiguous identification of a Tb β-delayed proton precursor. Decay studies of the new 16 ± 1 s ^{140}Gd were also performed.

A=141: We previously reported the observation of weak β-delayed proton activities from ^{141}Dy and ^{141}Gd [3]. A second experiment with improved statistics confirmed the previous Z assignments *via* coincident K x-rays and yielded half-lives of 0.9 ± 0.2 s and 16 ± 6 s, respectively, for the proton precursors. Gamma rays were observed in coincidence with the ^{141}Dy protons at 329 keV (2^+ to 0^+) and 508 keV (4^+ to 2^+) [6]. A spin determination of ^{141}Dy cannot be made at this time. From an analysis of the γ-rays populated in β-decay, a half-life of 20 ± 4 s for ^{141}Gd is in agreement with the β-delayed proton decay data and the value in ref. 7. This γ-ray analysis also resulted in the identification of the new isotope ^{141}Tb with a half-life of 3.5 ± 0.9 s.

A=142: A β-delayed proton activity with a single component half-life of 1.8 ± 0.6 s is assigned to the new isotope ^{142}Dy, on the basis of Tb K x-rays observed in coincidence with the protons. Independent analysis of the decay of the Tb x-rays and associated γ-rays results in a ^{142}Dy half-life of 2.3 ± 0.8 s (This is the value quoted in Table 1.). In the γ-decay analysis, two isomers of the previously unreported ^{142}Tb, with half-lives of 0.2 ± 0.1 s and 0.8 ± 0.4 s were also identified. The presence of Gd K x-rays in coincidence with protons in this mass chain may indicate a weak β-delayed proton branch in the decay of one of these isomers. However, 113 kev γ-rays, also seen in coincidence with the protons, were independently identified with a low-lying transition in ^{141}Gd. Hence, at least some of the Gd x-rays can be accounted for by internal conversion of these γ-rays (and possibly of more highly converted transitions not seen in the coincident spectrum), emitted from states populated in the β-delayed proton decay of ^{142}Dy. Relative intensity balance and proton decay analysis of presently available data can neither unambiguously confirm nor exclude the possibility of a β-delayed proton activity in ^{142}Tb decay.

A=144: A short lived proton emitter with a half-life of 0.7 ± 0.1 s was assigned to the new isotope ^{144}Ho on the basis of Dy K x-rays observed in coincidence with the protons. A second β-delayed proton activity with a half-life of 7 ± 3 s can be assigned to the new isotope ^{144}Dy [7,8] on the basis of Tb K x-rays observed in coincidence with the protons. The β-decay of ^{144}Dy yields a half-life of 9.2 ± 0.6 s from the decay of the most intense γ-rays in agreement with the half-life for the protons and the value in ref. 7. From decay data, a half-life of 4.1 ± 0.2 s for ^{144m}Tb was observed in agreement with ref. 9. No conclusive evidence for a β-delayed proton branch in ^{144m}Tb was obtained.

A=146: Dy K x-rays coincident with a 3.1 ± 0.5 s proton activity established for the first time β-delayed proton decay in ^{146}Ho.

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TABLE 1.

E_{lab} = bombarding energy; $T_{1/2}$ = weighted half-life from all available OASIS data, the value in the text may differ in some cases; $\bar{E}_p$ [Range] = average energy and energy range of the observed β-delayed protons.

ISOTOPE	REACTION	E_{lab} (MeV)	$T_{1/2}$ (s)	$\bar{E}_p$ [Range] (MeV)
^{124}Pr	^{92}Mo(^{36}Ar,p3n)	174	1.2 ± 0.2	3.7[2.1 - 5.9]
^{125}Ce	^{92}Mo(^{36}Ar,2pn)	153	9.2 ± 1.0	3.3[1.7 - 5.1]
^{127}Nd	^{92}Mo(^{40}Ca,2p3n)	208	1.8 ± 0.4	3.7[2.2 - 6.0]
^{131}Nd	^{94}Mo(^{40}Ca,2pn)	168	25 ± 4	3.1[1.7 - 6.4]
^{131}Sm	^{96}Ru(^{40}Ca,2p3n)	208	1.2 ± 0.2	3.7[1.8 - 6.6]
^{140}Tb	^{92}Mo(^{54}Fe,3p3n)	298	2.4 ± 0.4	4.2[2.2 - 6.6]
^{141}Gd	^{92}Mo(^{54}Fe,4pn)	276	20 ± 4	3.6[2.2 - 4.9]
^{141}Dy	^{92}Mo(^{54}Fe,2p3n)	276	0.9 ± 0.2	4.1[2.1 - 7.2]
^{142}Dy	^{92}Mo(^{54}Fe,2p2n)	247	2.3 ± 0.8	3.9[2.5 - 5.2]
^{144}Dy	^{92}Mo(^{56}Fe,2p2n)	245	9.1 ± 0.5	3.2[2.6 - 4.5]
^{144}Ho	^{92}Mo(^{58}Ni,3p2n)	325	0.7 ± 0.1	4.2[2.2 - 7.0]
^{146}Ho	^{92}Mo(^{58}Ni,2p2n)	261	3.1 ± 0.5	4.1[2.4 - 6.3]