PHYSICAL REVIEW C **93**, 024315 (2016)

Investigation of ^{88}Y via $(p,d\gamma)$ reactions

R. O. Hughes,[1] J. T. Harke,[1] R. J. Casperson,[1] J. E. Escher,[1] S. Ota,[1] J. J. Ressler,[1] N. D. Scielzo,[1] R. A. E. Austin,[2] B. Abromeit,[3] N. J. Foley,[3] E. McCleskey,[3] M. McCleskey,[3] H. I. Park,[3] T. J. Ross,[4] and A. Saastamoinen[3]
[1]*Nuclear and Chemical Sciences Division, Lawrence Livermore National Laboratory, Livermore, California 94551, USA*
[2]*Department of Physics, St. Mary's College, Halifax, Nova Scotia, Canada*
[3]*Cyclotron Institute, Texas A&M University, College Station, Texas 77840, USA*
[4]*Department of Physics, University of Richmond, 28 Westhampton Way, Richmond, Virginia 23173, USA*
(Received 17 December 2015; published 18 February 2016)

The low-spin structure of odd-odd ^{88}Y has been studied via $(p,d\gamma)$ reactions on an ^{89}Y target. The K150 Cyclotron at the Texas A&M University Cyclotron Institute was employed to provide a 28.5-MeV proton beam, and particle-γ and particle-γ-γ coincidence data were collected with the STARLiTeR array. A number of new levels and γ rays have been observed below 2.5 MeV, while level and γ-ray energies as well as spin-parity assignments have been re-evaluated.

DOI: 10.1103/PhysRevC.93.024315

I. INTRODUCTION

Measurements of neutron-induced cross sections for yttrium isotopes nearby monoisotopic ^{89}Y are of importance in stockpile stewardship applications but are difficult due to the short half-lives of the isotopes involved. For example, direct measurements of the ^{87}Y(n,γ) cross section are impractical due to the 80-h half-life of ^{87}Y. It is thus desirable to deduce the cross section indirectly by utilizing the surrogate method [1]. The surrogate method populates the same compound nucleus (CN) as the neutron-induced reaction of interest (in this case, ^{88}Y) by using a stable beam and target combination. However, it is known that the Weisskopf-Ewing approximation [2] typically used in surrogate applications breaks down for (n,γ) cross-section measurements due in large part to the difference in the spin imparted to the CN in the direct and surrogate reactions [3–6]. Efforts to correct for these differences with reaction models (for the CN formation) and statistical models (for the CN decay) are ongoing. An important factor in the efficacy of the necessary models is a detailed understanding of the low-lying nuclear structure in the daughter nucleus populated in the direct and surrogate reaction; in particular, precise spin-parity assignments and γ-ray decay branching ratios for levels below about 2 MeV excitation energy are crucial.

The nucleus ^{88}Y has 49 neutrons and 39 protons. It lies one nucleon away from the $N = 50$ shell closure and the $Z = 40$ subshell closure with low-lying structure that is predominantly single-proton and single-neutron in origin. The odd-odd nature of ^{88}Y leads to a complex structure with many excited states below 2 MeV. Analysis of the decay scheme of ^{88}Y is further complicated by the presence of several isomers at low energy. As a result, while numerous states have been identified in both low-spin [7–13] and high-spin [14–16] studies, many inconsistencies remain and the known structure below 2 MeV remains incomplete. The present work aims to improve the nuclear structure information of this nucleus by utilizing particle-γ coincidence analysis.

II. EXPERIMENTAL PROCEDURE

A 28.5-MeV beam provided by the K150 Cyclotron at the Texas A&M University Cyclotron Institute was used to bombard an ^{89}Y target (0.76 mg/cm^2 thickness, 19 mm diameter). Targets of ^{90,91,92,94,96}Zr and ^{nat}C were also irradiated during the experiment (see Ref. [17]) although these are not the focus of the present work. A solid phosphor target and camera were utilized to establish that the beam was focused on the target position. The beam spot had a Gaussian profile that was contained within a diameter of no more than 5 mm. The silicon telescope array for reaction studies (STARS), comprising a 140-μm-thick ΔE and two 1000-μm-thick E S2-type silicon detectors, was utilized for the detection of outgoing protons, deuterons, and tritons, while coincident γ rays were detected with five HPGe clover detectors in the Livermore-Texas-Richmond (LiTeR) array. The ΔE and two E detectors were placed behind the target position at 19.2, 23.4, and 33.8 mm, respectively, with the beam traveling through the center of the 22-mm-diameter annulus of each detector. Each silicon detector is segmented into 48 0.5-mm-wide concentric rings on one side and 16 sectors on the other to provide angular sensitivity. For this experiment, consecutive rings and sectors were bussed into 24 and 8 elements, respectively. With the present configuration, the telescope covered an angular range between about 25° and 55°. Data were collected for 81.8 h on ^{89}Y.

The silicon detectors were calibrated at the beginning and end of the experiment with a ^{226}Ra source, while the γ-ray sources ^{22}Na, ^{137}Cs, ^{54}Mn, ^{109}Cd, ^{60}Co, and ^{133}Ba were used for clover energy and efficiency calibrations. The γ-ray energy resolutions were typically ~1.3 keV 1σ below 500 keV, ~1.7 keV 1σ at 1 MeV, and ~2.5 keV 1σ at 2 MeV. Particle data were sorted with a requirement that events in the ΔE and E detectors were correlated, and valid events were ray traced to ensure that they originated from the target position. Protons, deuterons, and tritons could be differentiated by the relative energy loss in the silicon detectors. Deuterons were generally stopped in the first E detector, with only deuterons at the highest energies (corresponding to excitation energies below about 1 MeV) punching through into the second E detector, and only at low angles. Deuteron energies were converted into nuclear excitation energy by accounting for deuteron energy losses in dead layers (the target, δ-electron shield, and detector dead layers), the reaction Q value, and the nuclear recoil. The

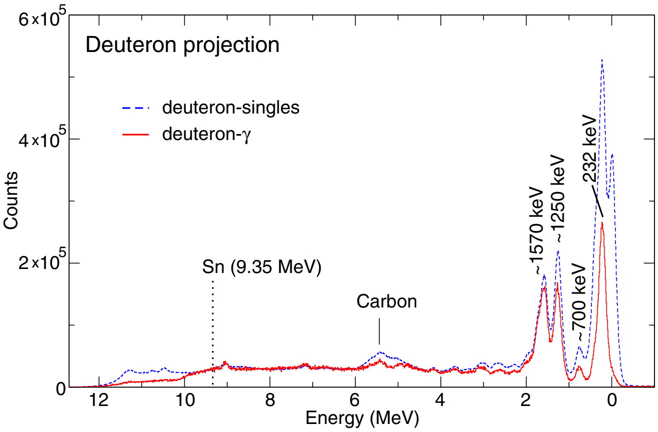

FIG. 1. Spectrum showing nuclear excitation energies associated with scattered deuterons measured for the $^{89}Y(p,d)$ reaction both as singles (dotted line) and in coincidence with γ rays (solid line). The deuteron-γ data are normalized to the deuteron-singles data for clarity. The large peaks below 2 MeV correspond to clusters of discrete states and are labeled with the approximate excitation energy of each cluster of levels. At higher excitation energy a carbon contaminant peak as well as the neutron separation energy, S_n, are indicated.

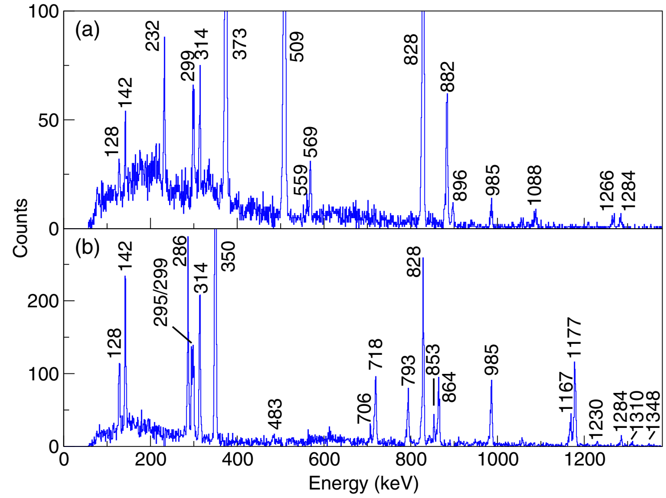

FIG. 2. Spectra showing γ rays observed in coincidence with peaks in the deuteron energy spectrum (as indicated in Fig. 1) that represent clusters of states populated directly in the $^{89}Y(p,d)^{88}Y$ reaction. (a) The deuteron peak at 1250 keV in Fig. 1 shows coincidences with γ rays associated with several discrete states including the 1221-, 1266-, 1275-, 1284-, and 1320-keV levels. (b) The deuteron peak at 1570 keV in Fig. 1 is in coincidence with γ rays associated with the decay of levels including the 1560-, 1570-, 1580-, and 1703-keV states.

uncertainty in the deduced excitation energies was measured by fitting the widths of discrete states in the particle data and these were observed to have an 80-keV 1σ uncertainty. This uncertainty originates from the intrinsic silicon detector resolutions (40–50 keV), energy straggling in dead layers ($\sim$ 20 keV), the uncertainty in the kinematic recoil correction ($\sim$20 keV), and approximately 60-keV energy resolution for the cyclotron beam energy. Deuteron-γ data were selected, with 2.6×10^6 coincidence events for ^{88}Y. In-house software was used to construct spectra and coincidence matrices for analysis with the RADWARE software package [18].

III. RESULTS

In order to investigate the low-lying structure of ^{88}Y, the deuteron-γ and deuteron-γ-γ data were analyzed. Figure 1 presents nuclear excitation energies measured in the $^{89}Y(p,d)$ reaction with deuterons populating ^{88}Y up to the neutron separation energy, S_n, at 9.35 MeV. Below 2 MeV, a number of peaks representing clusters of discrete states are labeled with their approximate energies. The peaks at 1250 and 1570 keV contain several directly populated levels. Figures 2(a) and 2(b) present γ-ray spectra showing the coincidences with the 1250- and 1570-keV peaks from Fig. 1, respectively.

A partial decay scheme for ^{88}Y was constructed by examining the coincidences between deuterons associated with directly populated nuclear states and the observed γ-ray cascades depopulating those states. The coincidence analysis led to the observation of several previously unmeasured levels and γ-ray transitions. The analysis also enabled the re-evaluation of the energies for several levels and transitions. Energy assignments for both the γ rays and excited states made use of the higher energy-resolution γ-ray data wherever possible. The revised decay scheme for ^{88}Y is presented in Fig. 3. Red horizontal lines and arrows represent newly observed energy levels and γ rays.

A. Summary of energy levels and γ rays associated with ^{88}Y

Table I lists properties of levels and γ-ray transitions associated with ^{88}Y in the present work. The table includes the level energies, E_{LEV}, spin and parities, J^π, γ-ray energies, E_γ, measured γ-ray branching ratios from each level, I_γ, and state population intensities, I_{LEV}. For I_γ, relative γ-ray intensities for a given level were measured in spectra produced from appropriate particle gates in the deuteron-γ data, were corrected for the photo-peak efficiency of the detector array, and were normalized so that the most intense γ ray from a given level is $I_\gamma = 100$. For I_{LEV}, the intensity of the discrete deuteron peak is taken from a coincidence spectrum gated on the most strongly observed γ ray from that level and is corrected for the photo-peak efficiency of the detector array and γ-ray branching ratios after taking into account conversion coefficients for each γ-ray branch obtained from Ref. [19]. Each value of I_{LEV} is given relative to the population of the 232-keV level which is normalized to $I_{LEV} = 100(8)$.

B. States of interest

Assignments to new and existing levels of unknown J^π were made based upon γ-ray decay selection rules for γ rays connecting the state of unknown J^π to known states. In general this method can restrict the J^π assignments but cannot provide unambiguous assignments.

To make more definitive assignments, measurements of the angular distribution of the charged particles involved in

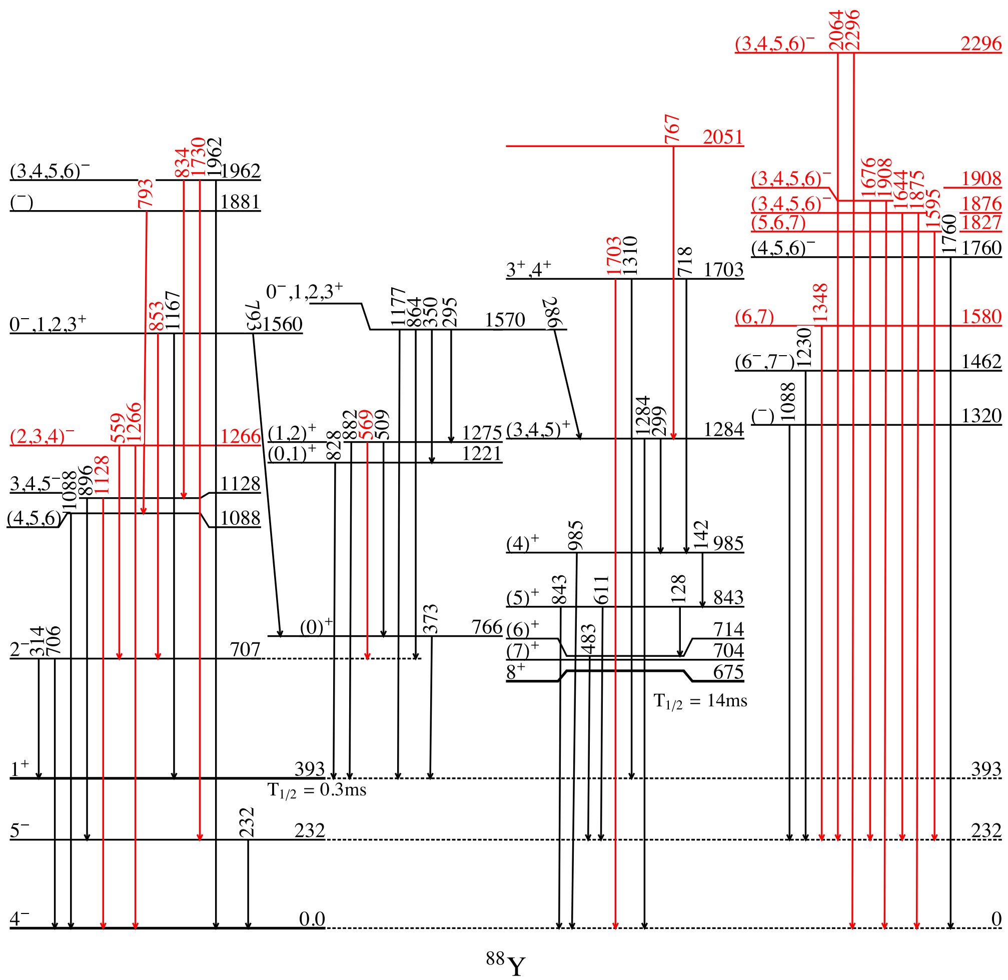

FIG. 3. Proposed level scheme for ^{88}Y. Red lines and arrows represent newly observed levels and γ rays.

direct population of discrete states (for L transfer values), and angular-correlations of γ-ray multipolarities would be useful. Unfortunately, in the present work, low statistics prevent these methods from being applied except in the case of intensely populated states and strong γ-ray transitions where such measurements have previously been performed. For instance, Comfort *et al.* [7] performed angular distribution measurements for ^{88}Y via (p,d) reactions and at a similar beam energy to the present experiment. Their results included L transfer values for all of the intensely populated states ($I_{LEV} > 10$ in Table I) observed in the present work.

1. 1266-keV level

This newly observed level exhibits 559- and 1266-keV decays to the 2^-, 707-keV level and 4^- ground state, respectively. It is suggested that this state has a spin and parity $J^\pi = (2,3,4)^-$.

2. 1560-keV level

This level decays via 793-, 852-, and 1166-keV transitions to the 766-keV $(0)^+$, 707-keV 2^-, and 393-keV 1^+ states, respectively. Based upon the observed decays, the 1560-keV state has possible assignments of $J^\pi = 0^-,1,2,3^+$.

3. 1570-keV level

Transitions with energies of 286, 295, 350, 864, and 1177 keV are observed to the 1284-keV $(3,4,5)^+$, 1275-keV $(1,2)^+$, 1221-keV $(0,1)^+$, 707-keV 2^-, and 393-keV 1^+ states, respectively. An assignment of $J^\pi = 0^-,1,2,3^+$ is suggested. A 1575-keV level reported in the literature and an associated 867-keV γ ray have not been observed. The 867-keV transition was reported as tentative [9] and has not been observed in other experiments. The 1575-keV level assignment was based upon charged particle experiments [7,10] with uncertainties up to 5 keV. It is possible that the reported 1575-keV level is in fact the same level as the 1570-keV state reported here.

4. 1580-keV level

Analysis of the deuteron-γ-γ data indicate a coincidence between a 1348-keV transition from the 1580-keV state and the 232-keV transition from the 5^- level at 232 keV. This transition, along with nonobservation of a direct decay to the 4^- ground state, suggests that $J = (6,7)$ is most likely for the 1580-keV level.

TABLE I. Transitions assigned to ^{88}Y. Level energies, E_{LEV}, spin and parities, J^{π}, γ-ray energies, E_{γ}, measured γ-ray branching ratios from each level, I_{γ}, and state population intensities, I_{LEV}, are shown for each state observed in the present work.

E_{LEV} (keV)	J^{π}	E_{γ} (keV)	I_{γ}	I_{LEV}
0	4^-			72(11)[a]
231.927(25)	5^-	231.9(1)		100(8)
392.86(9)	1^+			38(8)[a]
674.55(4)	8^+			
703.8(2)	$(7)^+$			
706.79(13)	2^-	313.9(1)	100(8)	1.5(3)
		706.3(5)	14(3)	
707.4(4)	$1^+,2^+,3^+$			
714.4(3)[b]	$(6)^+$	482.5(3)[b]	10(3)[c]	
766.22(16)	$(0)^+$	373.3(2)		
843.0(12)	$(5)^+$	128.0(1)	100(8)	
		611.0(2)	51(5)	
		843.0(3)[b]	32(4)	
984.66(13)	$(4)^+$	141.6(1)	39(4)	
		984.7(3)[b]	100(8)	
1088.2(1)	$(4,5,6)^-$	1088.2(1)		0.5(3)
1128.0(3)[b]	$3^-,4^-,5^-$	896.1(3)[b]	100(9)	3.0(6)
		1128.0(4)[d]	6(2)	
1220.6(2)[b]	$(0,1)^+$	827.7(2)[b]		22(3)
1266.0(3)[d]	$(2,3,4)^-$	559.1(4)[d]	21(5)	0.8(4)
		1266.0(4)[d]	100(11)	
1275.09(18)	$(1,2)^+$	508.9(1)	100(8)	38(4)
		882.1(2)	20(2)	
		568.5(3)[d]	5(1)	
1283.8(1)	$(3,4,5)^+$	299.1(1)	100(10)	1.1(3)
		1283.7(3)[b]	41(8)	
1320.13(10)	$^-$	1088.2(1)		0.4(2)
1461.6(3)	$(6^-,7^-)$	1229.7(3)		0.4(2)
1476.86(13)	9^+	802.3(2)		
1559.5(2)[b]	$0^-,1,2,3^+$	793.1(2)[b]	100(9)	6.8(13)
		852.7(3)[d]	41(6)	
		1166.7(3)[b]	91(9)	
1570.2(2)[b]	$0^-,1,2,3^+$	286.2(2)[b]	25(3)	31(4)
		294.8(3)[b]	13(2)	
		349.57(8)	100(8)	
		863.5(2)[b]	29(3)	
		1177.3(3)	57(5)	
1579.6(4)[d]	(6,7)	1347.7(4)[d]		0.2(1)
1702.6(2)[b]	$3^+,4^+$	717.9(2)	100(8)	17(2)
		1309.8(5)[b]	6(1)	
		1702.7(7)[d]	2(1)	
1760(1)[b]	$(4,5,6)^-$	1760.1(7)[b]		0.6(3)
1826.8(4)[d]	(5,6,7)	1594.9(4)[d]		0.5(3)
1875.6(4)[d]	$(3,4,5,6)^-$	1643.7(4)[d]	100(14)	1.1(4)
		1875(1)[d]	10(5)	
1881.1(3)[b]	$(^-)$	792.9(3)[d]		0.2(1)
1908.1(4)[d]	$(3,4,5,6)^-$	1676.2(3)[d]	100(14)	1.4(6)
		1907.9(5)[d]	46(7)	
1961.7(5)[b]	$(3,4,5)^-$	1962.3(5)[b]	100(13)	4.4(11)
		1730(1)[d]	6(3)	
		833.7(4)[d]	11(2)	
2050.5(3)[d]		766.7(3)[d]		2.3(5)
2296.2(8)[d]	$(3,4,5,6)^-$	2064.4(8)[d]	100(17)	0.1(1)
		2295.8(12)[d]	16(10)	

[a]Determined from the relative population of this level and the 232-keV state in particle-singles data.
[b]Measured level or γ-ray energy has been re-evaluated.
[c]Determined based on an intensity balance between the 483- and 128-keV transitions: see text.
[d]Newly observed energy level or γ ray.

5. 1703-keV level

This level exhibits 718- and 1310-keV decays and a newly observed 1703-keV decay to $(4)^+$, 1^+, and 4^- states, respectively. The J^{π} value was previously restricted to $J^{\pi} = 3^+, 4^+$. Transitions of 481- and 862-keV reported in Ref. [12] were not observed in coincidence with this level decay.

6. 1827-keV level

The 1827-keV level decays by a 1594-keV transition to the 5^- level at 232 keV. A potential 1827-keV transition to the ground state is not observed; however, an 1830-keV transition is seen which is more likely to be associated with the 1832(2)-keV level reported in the literature. While is is possible that both the 1827- and 1832(2)-keV levels are populated in this experiment, only the former can be assigned unambiguously based upon an observed coincidence between the 232- and 1594-keV γ-ray transitions in the particle-γ-γ data. The spin for the 1827-keV level is likely to be in the range $J = 5$–7.

7. 1876-keV level

This level decays via 1644- and 1875-keV transitions to the first excited, 5^- level at 232 keV and the 4^- ground state, respectively. It is possible that this is the same level reported at 1881(5) keV [7]. The spin and parity is most likely restricted to $J^{\pi} = (3,4,5,6)^-$ based upon the observed decays.

8. 1908-keV level

Decays to the ground state and first excited state are observed with energies of 1908 and 1676 keV. This level may be associated with the 1913(5)-keV level reported in Ref. [7]. As with the 1266- and 1875-keV levels, $J^{\pi} = (3,4,5,6)^-$ is likely.

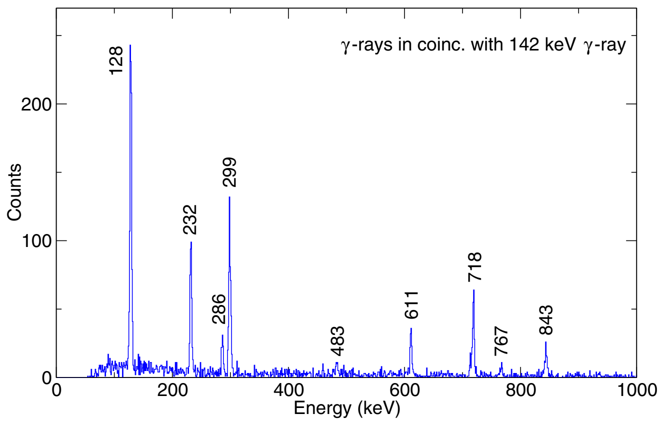

FIG. 4. Spectrum showing γ rays in prompt coincidence with a deuteron and the 142-keV γ decay in ^{88}Y.

9. 1962-keV level

This level was observed in previous $(p,d\gamma)$ work [13]. It is populated with significant strength and two new decays from this level have been observed in addition to the previously reported 1962-keV decay to the 4^- ground state. Transitions to the $3,4,5^-$ level at 1129 keV and the 5^- first excited state at 232 keV help restrict the spin and parity to $J^\pi = (3,4,5,6)^-$.

10. 2051-keV level

This level is directly populated with reasonable intensity. It exhibits a single, 767-keV decay to the $(3,4,5)^+$ level at 1284 keV. The level may be associated with the 2056(5)-keV level reported in Ref. [7]. Unfortunately the spin and parity for this level is ambiguous.

11. 2296-keV level

The 2296-keV level exhibits decays to both the ground state and first excited state. This level may possibly be associated with the 2305-keV level previously reported [7]. The probable spin-parity range is $J^\pi = (3,4,5,6)^-$.

12. The 714-keV level

Figure 4 shows a γ-ray spectrum requiring prompt coincidence with both a deuteron of any energy as well as the 142-keV transition from the 985-keV level. γ rays observed in the spectrum must therefore originate from ^{88}Y and either feed or be fed by the 985-keV level, which the 142-keV transition de-excites (cf. Fig. 3).

According to the present literature, de-excitation of the 714-keV, $(6)^+$ level proceeds via a single 483-keV transition to the 5^- level at 232 keV. If this is indeed the case, the coincidence requirement of the 142-keV γ ray for the spectrum in Fig. 4 necessitates that the total intensities of the 128- and 483-keV transitions should be equal. As can be seen in the figure, the 483-keV transition is much less intense than the 128-keV decay. Taking the measured γ-ray intensities for the 128- and 483-keV transitions in Fig. 4, and correcting for the relative energy efficiencies and internal conversion coefficients (assuming pure $M1$ and $E1$ multipolarity, respectively) from BRICC [19], the 483-keV transition exhibits 10(3)% of the total intensity of the 128-keV transition.

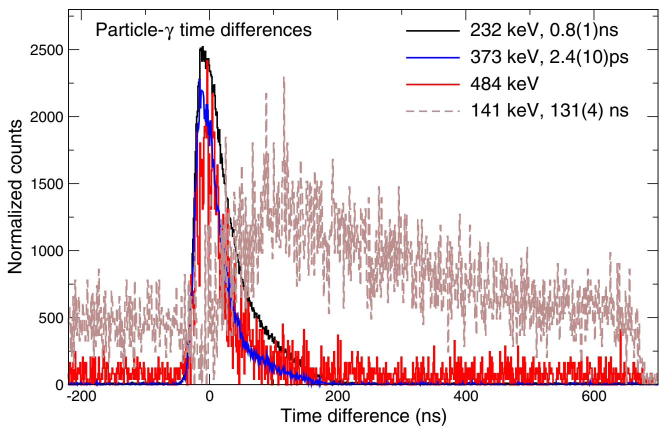

FIG. 5. Spectra showing deuteron-γ time differences for 232-, 373-, and 483-keV transitions in ^{88}Y and the 141-keV transition populated in ^{90}Zr via the ^{92}Zr(p,dn) reaction. The 483-keV transition of interest exhibits a distribution consistent with a lifetime of less than a few nanoseconds for the 714-keV level.

There are two potential explanations for this discrepancy. Either the 142- and 483-keV transitions are not in prompt coincidence, for example, if the 714-keV level is isomeric, or unobserved decays from the 714-keV level, parallel to the 483-keV transition, carry 90% of the decay intensity.

The potential isomeric nature of the 714-keV level can be investigated by examining the particle-γ time difference data for the 483-keV decay. Figure 5 shows the time spectra produced for the 483-keV decay of interest, the 373-keV decay from the 766-keV level in ^{88}Y ($T_{1/2} = 2.4(10)$ps), the 232-keV decay from the first excited state in ^{88}Y ($T_{1/2} = 0.8(1)$ns), and the 141-keV transition from the 3589-keV level in ^{90}Zr ($T_{1/2} = 131(4)$ ns). The latter time dependence was obtained from the ^{92}Zr target data populated via the ^{92}Zr$(p,dn\gamma)^{90}$Zr reaction. The time curves associated with the 373- and 232-keV transitions indicate a prompt deuteron-γ time difference response but also indicate that lifetimes up to a few nanoseconds are indistinguishable (i.e., time differences below a few nanoseconds appear to be prompt). On the other hand, the 141-keV transition from the 3589-keV level clearly shows a decay curve of the order of hundreds of nanoseconds, as expected for this decay from a $T_{1/2} = 131(4)$ ns level. The 483-keV transition time curve is indistinguishable from the curves for the 373- and 232-keV transitions, implying a lifetime of no more than a few nanoseconds for the 714-keV level.

It can be concluded that 90% of the decay intensity from the 714-keV level remains unobserved. Inspection of the level scheme in Fig. 3 suggests possible 11- and 40-keV transitions to the 704- and 675-keV states, respectively; however, these low-energy transitions remain unseen.

IV. SUMMARY

Particle-γ coincidence analysis of ^{88}Y has been performed using data from an ^{89}Y$(p,d\gamma)^{88}$Y reaction which utilized the

STARLiTeR array and a 28.5-MeV proton beam from the K150 Cyclotron at Texas A&M University. The analysis has led to several new states and γ-ray assignments below 2.5 MeV. The 714-keV level was previously reported to decay via a single 483-keV transition; however, analysis of the present data indicates that the 714-keV level has an upper half-life limit of a few nanoseconds and that the 483-keV transition must in fact carry only 10% of the total decay intensity. This in turn leads to the conclusion that unobserved, low-energy transitions to the 8^+, 675-keV and $(7)^+$, 704-keV levels are likely to account for the other 90% of the decay intensity. This correction for the 714-keV level γ-ray branching ratio is significant for the CN decay models required for deducing the ^{87}Y(n,γ) cross section via the surrogate method. It also affects calculations of the (n,γ) production cross section for the isomeric state at 675 keV.

ACKNOWLEDGMENTS

The authors are grateful for the efforts of the Texas A&M University Cyclotron Institute's operations and facilities staff. Figure 3 for this article was created using the LevelScheme scientific preparation system [20]. This work was performed under the auspices of the US Department of Energy by Lawrence Livermore National Laboratory under Contract No. DE-AC52-07NA27344, the Department of Energy's NNSA Office of Defense Nuclear Nonproliferation Research & Development, the Texas A&M Cyclotron Institute under Grants No. DE-FG52-09NA29467 from NNSA and No. DE-FG02-93ER40773 from the DOE Office of Nuclear Physics, and the University of Richmond under Grants No. DE-NA0001801 from NNSA and No. DE-FG02-05ER41379 from the DOE Office of Nuclear Physics.

[1] J. E. Escher, J. T. Harke, F. S. Dietrich, N. D. Scielzo, I. J. Thompson, and W. Younes, Rev. Mod. Phys. **84**, 353 (2012).
[2] V. F. Weisskopf and D. H. Ewing, Phys. Rev. **57**, 472 (1940).
[3] N. D. Scielzo *et al.*, Phys. Rev. C **81**, 034608 (2010).
[4] C. Forssén, F. S. Dietrich, J. Escher, R. D. Hoffman, and K. Kelley, Phys. Rev. C **75**, 055807 (2007).
[5] J. E. Escher and F. S. Dietrich, Phys. Rev. C **81**, 024612 (2010).
[6] G. Boutoux *et al.*, Phys. Lett. B **712**, 319 (2012).
[7] J. R. Comfort, A. M. Nathan, W. J. Braithwaite, and J. R. Duray, Phys. Rev. C **11**, 2012 (1975).
[8] J. R. Comfort and J. P. Schiffer, Phys. Rev. C **4**, 803 (1971).
[9] H. W. Baer, R. L. Bunting, J. E. Glenn, and J. J. Kraushaar, Nucl. Phys. A **218**, 355 (1974).
[10] W. W. Daehnick and T. S. Bhatia, Phys. Rev. C **7**, 2366 (1973).
[11] F. S. Dietrich, M. C. Gregory, and J. D. Anderson, Phys. Rev. C **9**, 973 (1974).
[12] F. Gabbard, G. Chenevert, and K. K. Sekharan, Phys. Rev. C **6**, 2167 (1972).
[13] T. J. Ross, C. W. Beausang, R. O. Hughes, N. D. Scielzo, J. T. Harke, J. M. Allmond, C. T. Angell, M. S. Basunia, D. L. Bleuel, R. J. Casperson, J. E. Escher, P. Fallon, R. Hatarik, J. Munson, S. Paschalis, M. Petri, L. Phair, and J. J. Ressler, Phys. Rev. C **86**, 067301 (2012).
[14] E. K. Warburton *et al.*, J. Phys. G **12**, 1017 (1986).
[15] C. J. Xu, S. Y. Wang, C. Y. Niu, C. Liu, B. Qi, D. P. Sun, L. Liu, P. Zhang, Z. Q. Li, Z. Wang, X. G. Wu, G. S. Li, C. Y. He, Y. Zheng, B. B. Yu, C. B. Li, S. P. Hu, S. H. Yao, X. P. Cao, and J. L. Wang, Phys. Rev. C **86**, 027302 (2012).
[16] M. Bunce *et al.*, Phys. Rev. C **87**, 044337 (2013).
[17] S. Ota, J. T. Harke, R. J. Casperson, J. E. Escher, R. O. Hughes, J. J. Ressler, N. D. Scielzo, I. J. Thompson, R. A. E. Austin, B. Abromeit, N. J. Foley, E. McCleskey, M. McCleskey, H. I. Park, A. Saastamoinen, and T. J. Ross, Phys. Rev. C **92**, 054603 (2015).
[18] D. C. Radford, Nucl. Instr. Meth. Phys. Res. A **361**, 297 (1995).
[19] T. Kibedi, T. W. Burrows, M. B. Trzhaskovskaya, P. M. Davidson, and C. W. Nestor, Nucl. Instr. Meth. Phys. Res. A **589**, 202 (2008).
[20] M. A. Caprio, Comput. Phys. Commun. **171**, 107 (2005).