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Spectroscopy of ^{88}Y by the $(p, d\gamma)$ reaction

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Low-spin, high-excitation energy states in ^{88}Y have been studied using the ^{89}Y$(p, d\gamma)$ reaction. For this experiment a 25 MeV proton beam was incident upon a monoisotopic ^{89}Y target. A silicon telescope array was used to detect deuterons, and coincident γ rays were detected using a germanium clover array. Most of the known low-excitation-energy low-spin states populated strongly via the (p, d) reaction mechanism are confirmed. Two states are seen for the first time and seven new transitions, including one which bypasses the two low-lying isomeric states, are observed.

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Recently the $A \sim 80$ mass region has attracted much attention due to the wealth of significant nuclear structure effects that have been unveiled including signature inversion, shape coexistence, and chiral doublet bands [1–4]. While these effects require knowledge of the high-spin and high-excitation-energy structures, [5,6], it is also of great importance to understand the lower spin structure of these nuclei. ^{88}Y with 39 protons and 49 neutrons is a doubly odd nucleus just one proton and one neutron away from the "closed-shell" nuclei ^{88}Sr and ^{90}Zr. Due to its monoisotopic nature, yttrium isotopes, and isotopes of neighboring nuclei including zirconium, have traditionally played a central role in applications including radiochemistry diagnostics [7,8]. For this application, measurements of neutron-induced cross sections on different isotopes in the region, particularly long-lived ones such as ^{88}Y, are desirable and, due to the low spins imparted by neutron-induced reactions, detailed knowledge of the low-spin, high-excitation energy level structure is of great interest. In particular, γ-ray decays which bypass long-lived isomeric states, typical in the region, are of interest for cross-section calculations. One method of measuring such cross sections is the surrogate reaction technique, [9]. Several studies throughout the 1970s and 1980s utilized light-ion transfer reactions to probe excited states in ^{88}Y [10–15]. In this Brief Report we discuss new results in ^{88}Y using the $(p, d\gamma)$ reaction.

The experiment was carried out at the 88-Inch Cyclotron at Lawrence Berkeley National Laboratory using the STARS-LIBERACE arrays [16]. A proton beam ($E_{\text{beam}} =$ 25 MeV, typical beam current ~2.5 enA) was incident upon a monoisotopic ^{89}Y target for a period of 90 min. In this work, focus is placed upon spectroscopy of discrete states in ^{88}Y, populated via the ^{89}Y$(p, d\gamma)$ reaction, utilizing the spectroscopic techniques recently demonstrated by Allmond *et al.* [17]. The combination of particle and γ-ray detection provides several advantages over traditional γ-ray spectroscopy experiments such as providing reaction (and thus final product) selectivity, light-ion energy measurement (which can be used to deduce the resultant nuclear excitation energy), and light-ion angular distributions (providing information about the spin transfer). Here we demonstrate how such level building techniques can be used to great effect when conducting spectroscopy of traditionally *difficult* odd-odd nuclei.

These data were taken as part of a larger study of gadolinium isotopes by the (p, d) and (p, t) reactions and the setup is the same as that used in Ref. [18]. Outgoing light ions were detected with the silicon telescope array for reaction studies (STARS) [16] which consisted of two segmented silicon detectors arranged in a ΔE-E telescope configuration. Each silicon detector is segmented into 48 rings and 16 sectors. However, adjacent rings and sectors were bussed to give 24 rings and 8 sectors per detector. The ΔE detector was 150 μm thick and the E detector was 1000 μm thick. An aluminum absorber (150 μg/cm^2) was placed in front of the ΔE detector to absorb delta electrons. This absorber and the dead layers on the surface of the silicon detectors (0.1 μm aluminum on the front surface and 0.3 μm gold surface on the back) are taken into account in event-by-event energy loss calculations. The detector configuration was chosen so as to be thick enough to stop and measure the energy of deuterons and tritons leaving the target. In addition, protons with energy below ~19 MeV were also stopped by the ΔE-E telescope. Above ~19 MeV the protons had too much energy to be stopped by the silicon detectors and "punched through" the array.

The position information from the two silicon detectors is used to perform a ray trace back to the target. A measured

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particle is only considered if energy is deposited in both the ΔE and E detectors and the particle is deemed to have originated from the target position. The silicon detectors were energy calibrated at the beginning and end of the run using a ^{226}Ra source.

γ rays in coincidence with the detected particles were measured using the Livermore Berkeley array for collaborative experiments (LIBERACE) [16]. For this experiment, LIBERACE consisted of 5 HPGe clover detectors, each with its own bismuth germanate (BGO) Compton suppression shield. Two detectors were placed at 90°, two at forward angles of 50°, and one at a backward angle of 50° with respect to the beam. The germanium detectors were energy calibrated using standard γ-ray sources before and after the run. An energy resolution of $\sim$2 keV was achieved at 200 keV and $\sim$4.5 keV was achieved at $\sim$1.5 MeV. An efficiency calibration was carried out at the end of the experiment using ^{152}Eu, ^{133}Ba, and ^{207}Bi sources. The efficiency of the array peaked at 2.6% at $\sim$200 keV and drops to 1.25% at $\sim$1 MeV. Internal conversion coefficients were calculated using the BRICC code [19]. A total of 7.4×10^5 deuteron events and 6.6×10^4 deuteron-γ coincidence events were recorded.

The projection of deuterons measured in coincidence with all γ rays is shown in Fig. 1 (dashed spectrum). The peak just above zero excitation energy almost all corresponds to the direct population of the first excited 5^- state at 231 keV. The expected large (p, d) population of the ground state does not appear due to the prompt γ-ray coincidence requirement. Similarly, peaks corresponding to the direct population of the two low-lying isomers at 393 keV ($t_{1/2} = 0.3$ ms) and 674 keV ($t_{1/2} = 13.97$ ms) are also not apparent in this spectrum. Most of the observed states which are directly populated are in the excitation-energy region between 1 and 2 MeV (see Fig. 1).

The spectrum of γ rays which decay from states with excitation energies between 1 and 2.1 MeV is shown in Fig. 2. The excitation energy "gate" utilized is not selective of first-generation γ rays and thus coincident transitions which occur farther down the decay chain, from states below 1 MeV are also observed. For example, the 231 keV γ ray shown in Fig. 2(a) is the transition from the 5^- 231 keV level to the ground state.

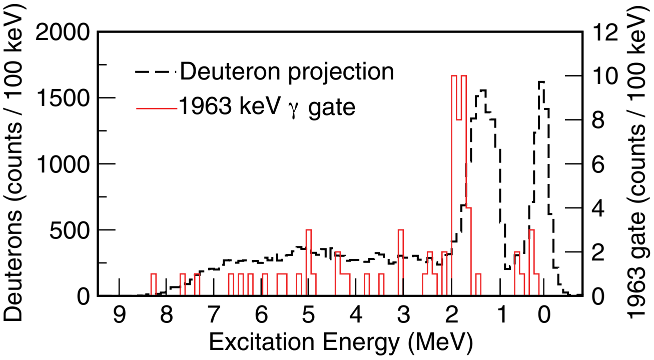

FIG. 1. (Color online) Dashed spectrum: The projection of the deuterons in coincidence with all detected γ rays. Solid spectrum: The deuterons in coincidence with the 1963 keV γ ray.

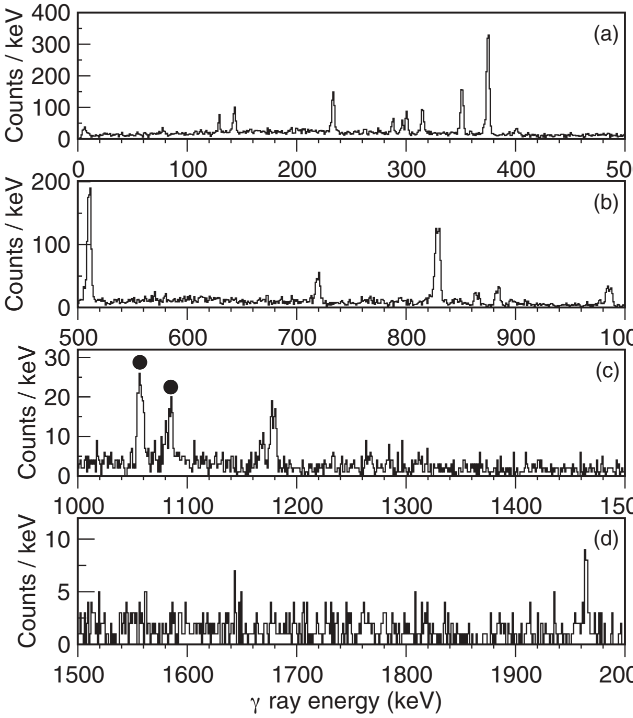

FIG. 2. γ rays in coincidence with population of the excitation energy region: $1 < E* < 2.1$ MeV, in ^{88}Y. Contaminant coincidences involving ^{88}Zr γ rays are labeled with solid black dots. (a) $0 < E_\gamma < 500$ keV. (b) $500 < E_\gamma < 1000$ keV. (c) $1000 < E_\gamma < 1500$ keV. (d) $1500 < E_\gamma < 2000$ keV.

Due to the very large $(p, 2n)$ cross section [20], the most intense decays in ^{88}Zr are also observed in random coincidence with deuterons. These lines are labeled in Fig. 2(c) by solid black dots and are distinguishable from γ rays of interest because they are in coincidence with *all* deuteron energies. Figure 3 shows the γ rays in coincidence with a gate placed upon the excitation energy region $0 < E* < 0.5$ MeV. The only transition one would expect to see in this gate is the very prominent 231 keV line.

Most of the previously known γ-ray transitions from low-lying states up to 1.8 MeV were observed [21]. In addition, two new levels and seven new γ rays were seen. A summary of the levels populated by the ^{89}Y$(p, d)^{88}$Y reaction is given in Table I. New information in this table is shown in bold font. Population yields are expressed relative to the most intensely populated state, the 5^- at 231 keV. The low-lying level scheme of ^{88}Y that we observe is presented in Fig. 4. Levels are labeled by their spins, parities, and excitation energies.

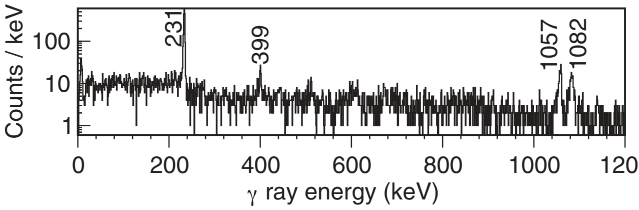

FIG. 3. γ rays in coincidence with population of the excitation energy region: $0 < E* < 500$ keV.

TABLE I. Summary of the levels populated and decays observed in ^{88}Y in the current work. Newly observed levels and transitions are shown in bold. E^* corresponds to the level energy, those not shown in bold are NNDC values [21]. J^π corresponds to the spin and parity of the level [21]. Yield$_{\mathrm{rel}}$ gives the yield for each state relative to the most intensely populated state at 231 keV. E_γ corresponds to the γ-ray energy as measured in this work. I_γ is the intensity of each γ ray relative to other decays leaving that level. E^*_{final} NDS is the adopted data sheet energy of the level to which the γ ray decays. J^π_{final} gives the spin and parity of the final level [21].

E^* (keV)	J^π	Yield$_{\mathrm{rel}}$	E_γ (keV)	I_γ	E^*_{final} NDS (keV)	J^π_{final}
0.0 (*0*)	4^-	-				
231.929 (*6*)	$(5)^-$	**100(0)**	231.84(*6*)	**100 (0)**	0.0 (*0*)	4^-
392.86 (*5*)	1^+	-				
674.55 (*7*)	$(8)^+$	-				
706.72 (*7*)	(2^-)	**1.5(4)**	314.05(*15*)	**100 (0)**	392.86 (*5*)	1^+
766.4 (*9*)	$(0)^+$	**11(1)**	373.22(*15*)	**100 (0)**	392.86 (*5*)	1^+
843.18 (*12*)	$(5)^+$	Fed	127.8(*2*)	**100(14)**	715.16 (*13*)	6^+
			611.2(*4*)	**42 (18)**	231.929 (*6*)	5^-
984.83 (*13*)	$(4)^+$	Fed	141.6(*2*)	**55 (5)**	843.18 (*12*)	$(5)^+$
			983.6(*3*)	**100(14)**	0.0 (*0*)	4^-
1129.13 (*5*)	3,4,5^-	**1.4(4)**	896.0(*6*)	**100 (0)**	231.929 (*6*)	$(5)^-$
1221.26 (*21*)	0,1^+	**22(2)**	827.6(*2*)	**100 (0)**	392.86 (*5*)	1^+
1275.3 (*7*)	1,2^+	**25(2)**	508.85(*9*)	**100 (6)**	766.4 (*9*)	(2^-)
			882.1(*3*)	**22 (3)**	392.86 (*5*)	1^+
1283.95 (*10*)	3,4,5	**1.1(7)**	299.2(*3*)	**100(27)**	984.83 (*13*)	$(4)^+$
			1283(*1*)	**43 (27)**	0.0 (*0*)	4^-
1559.3 (3)		**4.5(13)**	**793.2(8)**	**67(26)**	766.4(*3*)	$(0)^+$
			1166.2(5)	**100(20)**	392.86(*9*)	1^+
1570.1 (*3*)		**22.1(12)**	**286.2(8)**	**26(4)**	1283.95(*15*)	(3,4,5)
			295.1(3)	**14(3)**	1275.3(*10*)	$(1,2)^+$
			349.57(*8*)	**100(8)**	1221.26(*14*)	$(0,1)^+$
			863.0(4)	**27(5)**	706.72(*13*)	2^-
			1177.3(*3*)	**40(7)**	392.86(*9*)	1^+
1702.6 (*3*)	3^+,4^+	**9.4(21)**	717.85(*20*)	**100(12)**	984.83(*13*)	$(4)^+$
			1309.0(4)	**10(6)**	392.86(*9*)	1^+
1962.5 (4)		**3.0(6)**	**1962.5(4)**	**100(0)**	0.0(*0*)	4^-

Of particular interest is a new γ ray of energy $E_\gamma = 1962.5$ keV. The deuteron spectrum measured in coincidence with this γ ray is shown in Fig. 1 (solid spectrum), where the peak (corresponding to direct population of the state) corresponds to an excitation energy of 1948 ± 30 keV. The combination of γ-ray energy and excitation energy ($E_\gamma = 1962.5$ keV and $E^* = 1948 \pm 30$ keV) allows us to conclude that the only level to which this γ ray could possibly decay is the ground state. Therefore a new level is established at 1962.5 keV. This decay bypasses both of the low-lying isomers through which most of the γ-ray cascade passes. Other previously known states, whose decay bypasses the isomers (984, 1088, 1234, and 1262 keV) are not directly populated. The level at 984 keV is quite strongly fed by higher excitation energy states which are directly populated in this experiment. This level at 1963 keV is probably the same level observed by Taketani *et al.* [14] at 1.95 MeV, although no details are provided.

Several nearby nuclei, including ^{89}Y, also have γ-ray transitions with $E_\gamma \sim 1963$ keV. To confirm that the 1962.5 keV line observed here is indeed from ^{88}Y, the $(p, p'\gamma)$ data are utilized. The particle projection of ^{89}Y$(p, p')^{89}$Y inelastic scattering is shown by the dashed spectrum in Fig. 5. Excitation energy increases from right to left. The gate (solid spectrum) in Fig. 5(a) shows the protons in coincidence with the 1982 keV transition in ^{89}Y. As expected, this decay is only observed in coincidence with levels below the neutron separation energy. The gate (solid spectrum) in Fig. 5(b) shows the protons in coincidence with 231 keV transition in ^{88}Y. This decay is only observed in coincidence with levels above the neutron separation energy. The gate (solid spectrum) in Fig. 5(c) shows that a γ ray of energy 1963 keV is detected in both ^{89}Y and ^{88}Y, i.e., both above and below the neutron separation energy. The $\sim$2 MeV gap above the neutron separation energy is completely consistent with this conclusion and the placement of the 1963 keV level in ^{88}Y.

Information concerning several other states has been obtained. A series of γ rays is observed that decay from an excitation energy of $\sim$1550 keV, as determined by the coincident deuterons. The energies of these γ rays are 286, 295, 793, 863, and 1166 keV. Due to the low level density in the low-energy structure of ^{88}Y, there are only a few viable options for the placement of these decays. Three of these γ rays (286, 295, and 1166 keV) are assigned to the level at 1570 keV in addition to two previously measured decays from this level (350 and 1177 keV, these two γ-ray energies have been measured to a higher precision). This level is the fourth most intensely populated state by the (p, d) reaction.

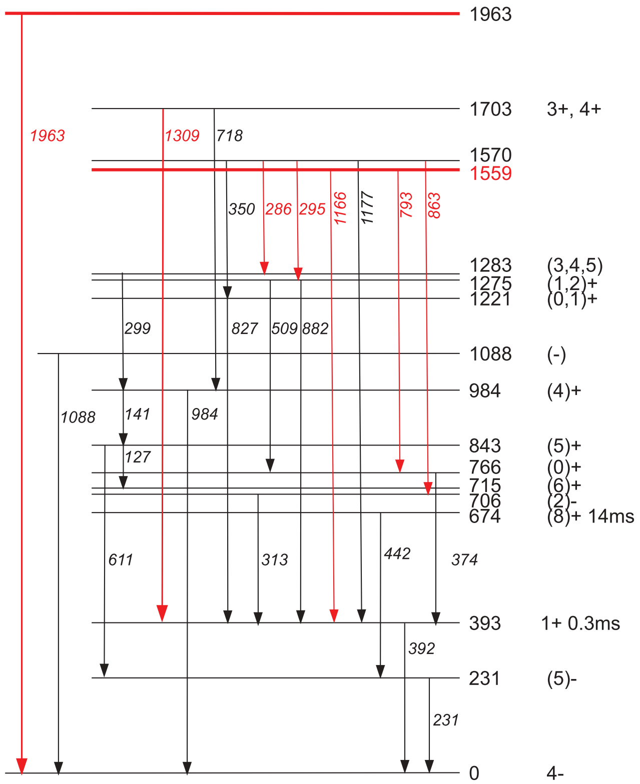

FIG. 4. (Color online) The low-lying level scheme of ^{88}Y observed in this work. New transitions and levels are shown in red if viewed online.

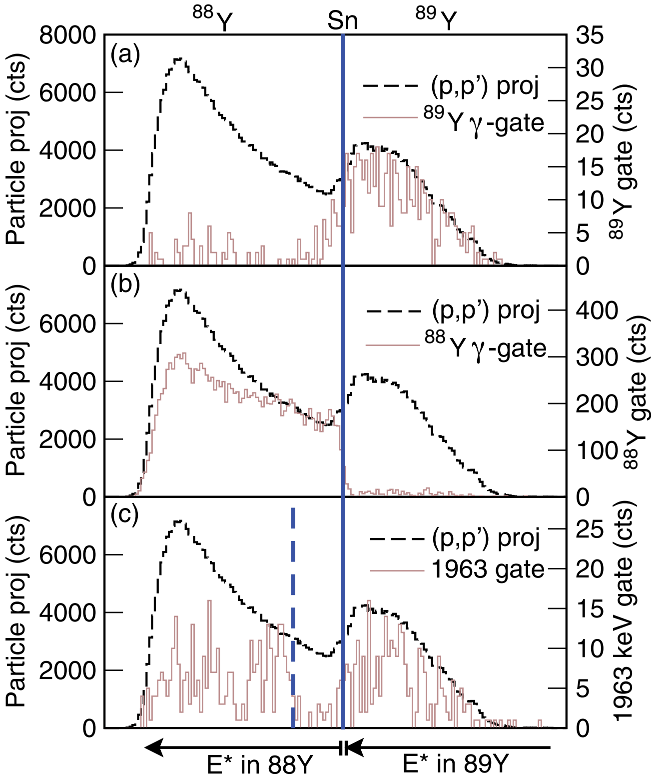

FIG. 5. (Color online) Dashed spectrum: The $(p, p')^{89}$Y proton energy spectrum. Solid vertical line: The ^{89}Y neutron separation energy, left of which the $(p, p'n)^{88}$Y reaction dominates. Solid spectrum shows (a) protons in coincidence with the 1982 keV transition in ^{89}Y, (b) protons in coincidence with the 231 keV transition in ^{88}Y, and (c) protons in coincidence with the 1963 keV γ ray energy of interest. In (c), the dashed vertical line signifies the point at which the excitation energy in ^{88}Y is greater than ~1900 keV.

The 793 and 1166 keV γ rays are assigned to a new level at 1559 keV. Both of these decays eventually pass through the 0.3 ms isomeric state at 393 keV. The two levels at 1559 and 1570 keV account for the strong population observed by Taketani *et al.* [14] around 1.56 MeV.

A 1309 keV transition originating from a state at ~1700 keV is assigned to the level at 1702.6 keV. This new transition is weak in comparison to the one previously known decay (718 keV) from this state.

In conclusion, the low-lying structure of ^{88}Y has been studied using particle-γ coincidence spectroscopy. Much of the known low-spin-level structure has been confirmed. Relative population yields of all states populated via the (p, d) reaction have been measured. Two new levels have been observed including a level at 1963 keV which bypasses both of the lower-lying isomeric states. That such clean spectroscopy was possible following just 90 min of beam on target suggests that a more comprehensive study of nuclei in the region utilizing similar techniques could be very useful. In particular, the use of angular distributions of outgoing light ions combined with the selectivity of a γ-ray gate would be able to help with spin and parity assignments for these historically difficult to study states.

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