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Spectroscopy of ^{88}Y by the (p,d-γ) reaction.

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Low-spin, high-excitation energy states in ^{88}Y have been studied using the ^{89}Y(p,d-γ) reaction. For this experiment a 25 MeV proton beam was incident upon a mono-isotopic ^{89}Y target. A silicon telescope array was used to detect deuterons and coincident gamma 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 by-passes 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]. Whilst 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 mono-isotopic 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, gamma-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 1970's and 1980's 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-γ) 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_{beam} = 25 MeV, typical beam current $\sim$ 2.5 enA) was incident upon a mono-isotopic ^{89}Y target for a period of ninety minutes. In this work, focus is placed upon spectroscopy of discrete states in ^{88}Y, populated via the ^{89}Y(p,d-γ) reaction, utilizing the spectroscopic techniques recently demonstrated by Allmond *et al.* [17]. The combination of particle and gamma-ray detection provides several advantages over traditional gamma-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.

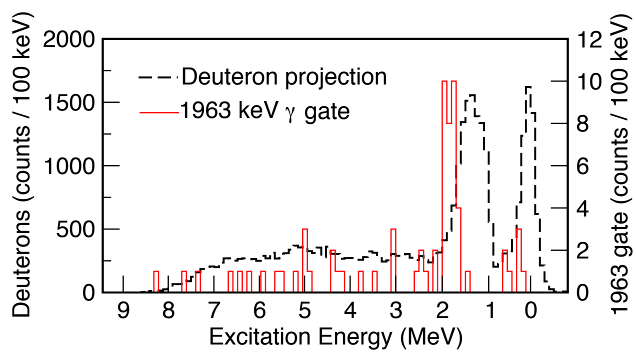

FIG. 1. (Color online) Dashed spectrum: The projection of the deuterons in coincidence with all detected gamma rays. Solid spectrum: The deuterons in coincidence with the 1963 keV γ ray.

This data was 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 [18]. Outgoing light ions were detected with the silicon telescope array for re-

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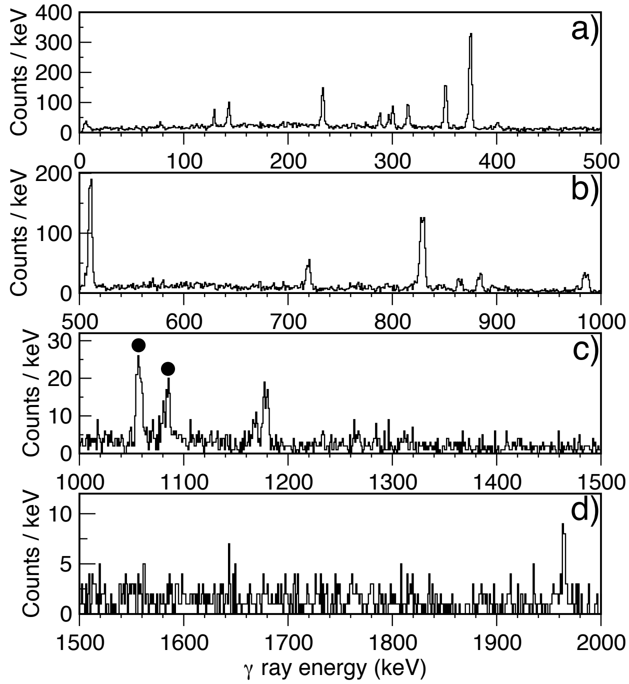

FIG. 2. Gamma rays in coincidence with population of the excitation energy region: 1 MeV < E* < 2.1 MeV, in ^{88}Y. Contaminant coincidences involving ^{88}Zr γ rays are labelled with solid black dots. (a) 0 keV < E_γ < 500 keV. (b) 500 keV < E_γ < 1000 keV. (c) 1000 keV < E_γ < 1500 keV. (d) 1500 keV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

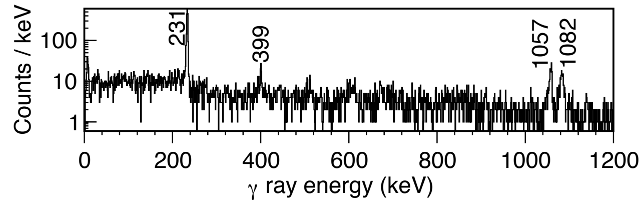

FIG. 3. Gamma rays in coincidence with population of the excitation energy region: 0 keV < E* < 500 keV.

action studies (STARS) [16] which consisted of two segmented silicon detectors arranged in a $\Delta E - E$ 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 $\mu g/cm^2$) 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 $\Delta E - E$ 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 particle is only considered if energy is deposited in both the ΔE and E detector 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.

Gamma 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 gamma ray sources before and after the run. An energy resolution of ∼ 2 keV was achieved at 200 keV and ∼ 4.5 keV was achieved at ∼ 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 ∼ 200 keV and drops to 1.25% at ∼ 1 MeV. Internal conversion coefficients were calculated using BrIcc, [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 gamma rays is shown in Fig. 1 (dashed spectrum). The peak just above zero excitation energy almost all corresponds to 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 gamma-ray coincidence requirement. Similarly, peaks corresponding to 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 gamma 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 gamma rays and thus coincident transitions which occur further down the decay chain, from states below 1 MeV are also observed. For example, the 231-keV gamma ray shown in Fig. 2 (a) is the transition from the 5^- 231-keV level to the ground state.

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 labelled in Fig. 2 (c) by solid black dots and are distinguishable from gamma rays of interest because they are in coincidence with *all* deuteron energies. Figure 3 shows the gamma

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$_{rel}$ 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. $E^*_{\rm final}$ NDS is the adopted data sheet energy of the level which the γ ray decays to. J^π_{final} gives the spin and parity of the final level, [21].

E^* (keV)	J^π	Yield$_{rel}$	E_γ (keV)	I_γ	$E^*_{\rm final}$ 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^-

rays in coincidence with a gate placed upon the excitation energy region, 0 MeV < 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 gamma-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 labelled by their spins, parities and excitation energies.

Of particular interest is a new gamma ray of energy E_γ = 1962.5 keV. The deuteron spectrum measured in coincidence with this gamma 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 gamma ray energy and excitation energy [E_γ = 1962.5 keV & E* = 1948 ± 30 keV], allows us to conclude that the only level that this gamma ray could possibly decay to 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 gamma-ray cascade passes. Other previously known states, whose decay bypass the isomers (984 keV, 1088 keV, 1234 keV 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.

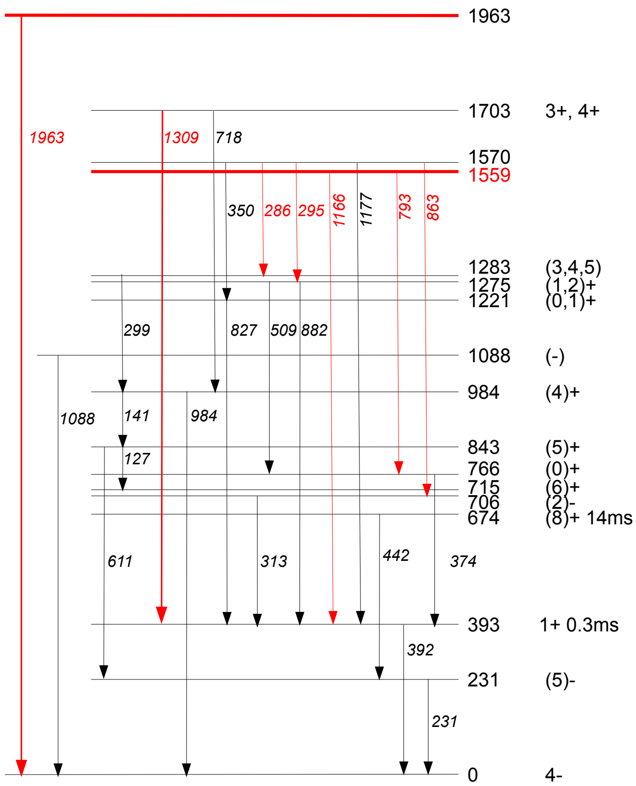

FIG. 4. (Color online) The low lying level scheme of ^{88}Y observed in this work is shown. New transitions and levels are shown in red if viewed online.

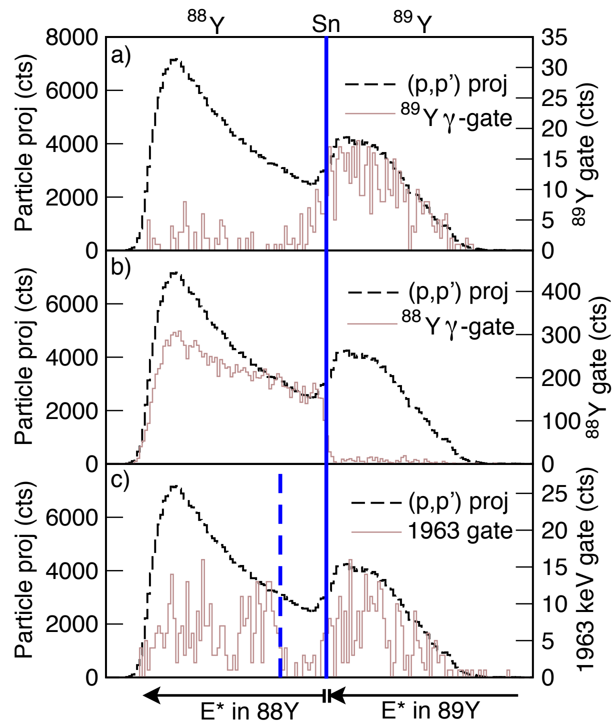

FIG. 5. (Color online) Dashed spectrum: The (p,p′)^{89}Y proton energy spectrum. Solid vertical line: Shows the ^{89}Y neutron separation energy, left of which the (p,p′n)^{88}Y reaction dominates. (a) Solid spectrum shows protons in coincidence with the 1982 keV transition in ^{89}Y. (b) Protons in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

Several nearby nuclei, including ^{89}Y, also have gamma-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′-γ) data is 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 (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 (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 (c) shows that a gamma 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 ~ 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 gamma rays are observed that decay from an excitation energy of ~ 1550 keV, as determined by the coincident deuterons. The energies of these gamma 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 gamma 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 keV and 1177 keV, these two gamma ray energies have been measured to a higher precision). This level is the fourth most intensely populated state by the (p,d) reaction.

The 793 keV and 1166 keV gamma 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 keV 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 ninety minutes 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 gamma ray gate would be able to help with spin and parity assignments for these historically difficult to study states.

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[1] C. Plettner *et al.* Phys. Rev. Lett. **85**, 2454 (2000)
[2] J. Ljungvall *et al.* Phys. Rev. Lett. **100**, 102502 (2008)
[3] R. Wadsworth *et al.* Phys. Lett. B **701**, 306 (2011)
[4] S.Y. Wang *et al.* Phys. Lett. B **703**, 40 (2011)
[5] M.R. Bunce *at al.* Journal of Physics: Conference Series **381** 012068 (2012)
[6] C.J. Xu *et al.* Phys. Rev. C **86**, 027302 (2012)
[7] E.D. Arthur. Tech. Report LA-7789-MS. Los Alamos National Laboratory, Los Alamos, NM (1977)
[8] R. D. Hoffman, K. Kelley, F. S. Dietrich, R. Bauer and M. G. Mustafa. UCRL-TR-222275. Lawrence Livermore National Laboratory, Livermore, CA (2006)
[9] J.E. Escher, J.T. Burke, F.S. Dietrich, N.D. Scielzo, I.J. Thompson and W. Younes Rev. Mod. Phys. **84**, 353, 027302 (2012)
[10] J.E. Kitching, P.A. Batay-Csorba, C.A. Fields, R.A. Ristinen and B.L. Smith. Nucl. Phys. **A302** p. 159-172 (1978)
[11] I. Levenberg, V. Pokrovsky, L. Tarasova, Van Cheng-Peng and I. Yutlandov. Nucl. Phys. **81** p. 81-87 (1966)
[12] W.W. Daehnick and T.S. Bhatia. Phys. Rev. C **7**, 6 (1973).
[13] F.S. Dietrich, M.C. Gregory and J.D. Anderson. Phys. Rev. C **9**, 3 (1974).
[14] H. Taketani, M. Adachi, M. Ogawa and K. Ashibe. Nucl. Phys. **A204** p. 385-411 (1973)
[15] J.R. Comfort, A.M. Nathan, W.J. Braithwaite and J.R. Duray. Phys. Rev. C **11**, 6 (1975)
[16] S. R. Lesher *et al.* Nucl. Instrum. Methods. A **621**, p. 286 (2010).
[17] J. M. Allmond *et al.* Phys. Rev. C **81**, 064316 (2010).
[18] T.J. Ross *et al.* Phys. Rev. C (R) **85**, 051304 (2012)
[19] T. Kibédi *et al.* Nucl. Instr. and Meth. A **589** p. 202-229 (2008)
[20] M.G. Mustafa, H.I. West, H. O'Brien, R.G. Lanier, M. Benhamou and T. Tamura. Phys. Rev. C **38**, 1624 (1988)
[21] G. Mukherjee, A.A. Sonzogni Nuclear Data Sheets **105**, 419 (2005)