



University of Richmond
UR Scholarship Repository

Physics Faculty Publications

Physics

4-30-2013

High-Spin Study of the Shell Model Nucleus $^{88}\text{Y}_{49}$

M. Bunce

P. H. Regan

V. Werner

C. W. Beausang

University of Richmond, cbeausan@richmond.edu

A. Anagnostatou

See next page for additional authors

Follow this and additional works at: <http://scholarship.richmond.edu/physics-faculty-publications>

 Part of the [Nuclear Commons](#)

Recommended Citation

Bunce, M., P. H. Regan, V. Werner, C. W. Beausang, V. Anagnostatou, M. Bowry, R. J. Casperson, D. Chen, N. Cooper, P. M. Goddard, R. O. Hughes, G. Ilie, P. J. R. Mason, B. Pauerstein, M. W. Reed, T. J. Ross, and E. C. Simpson. "High-Spin Study of the Shell Model Nucleus $^{88}\text{Y}_{49}$." *Physical Review C* 87, no. 4 (April 30, 2013): 044337: 1-44337: 8. doi:10.1103/PhysRevC.87.044337.

This Article is brought to you for free and open access by the Physics at UR Scholarship Repository. It has been accepted for inclusion in Physics Faculty Publications by an authorized administrator of UR Scholarship Repository. For more information, please contact scholarshiprepository@richmond.edu.

Authors

M. Bunce, P. H. Regan, V. Werner, C. W. Beausang, A. Anagnostatou, M. Bowry, R. J. Casperson, D. Chen, N. Cooper, P. Goddard, R. O. Hughes, G. Ilie, P.J.R. Mason, B. Pauerstein, M. W. Reed, T. J. Ross, and E. C. Simpson

High-spin study of the shell model nucleus $^{88}\text{Y}_{49}$

M. Bunce,^{1,*} P. H. Regan,¹ V. Werner,² C. W. Beausang,³ V. Anagnostatou,¹ M. Bowry,¹ R. J. Casperson,⁴ D. Chen,³ N. Cooper,² P. M. Goddard,¹ R. O. Hughes,³ G. Ilie,^{2,5} P. J. R. Mason,¹ B. Pauerstein,³ M. W. Reed,^{1,6} T. J. Ross,^{1,3} and E. C. Simpson¹

¹*Department of Physics, University of Surrey, GU2 7XH Guildford, England, United Kingdom*

²*Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06520-8120, USA*

³*Department of Physics, University of Richmond, Richmond, Virginia 23173, USA*

⁴*Lawrence Livermore National Laboratory, Livermore, California 94551, USA*

⁵*National Institute for Physics and Nuclear Engineering, R-77125 Bucharest-Magurele, Romania*

⁶*Department of Nuclear Physics, Research School of Physics and Engineering, Australian National University, Canberra 0200, Australian Capital Territory, Australia*

(Received 26 November 2012; revised manuscript received 30 January 2013; published 30 April 2013; publisher error corrected 11 July 2013)

The near-yrast structure of the near-magic, odd-odd nucleus, $^{88}_{39}\text{Y}_{49}$, has been studied into the high-spin regime. Investigations were performed at the Wright Nuclear Structure Laboratory, Yale University, using the $^{74}\text{Ge}(^{18}\text{O}, p3n)$ and $^{76}\text{Ge}(^{18}\text{O}, p5n)$ fusion-evaporation reactions at beam energies of 60 and 90 MeV, respectively. Gamma-ray energy coincidence analyses using both double (γ^2) and triple (γ^3) fold coincidences, together with angular correlation measurements, have been used to extend the previously reported level scheme to an excitation energy of 8.6 MeV and a spin and parity of 19^{-} . The presented level scheme is compared with predictions of a truncated valence space shell-model calculation, which assumes an inert ^{56}Ni core with proton and neutron excitations allowed within the $f_{5/2}$, $p_{3/2}$, $p_{1/2}$, and $g_{9/2}$ single-particle states. The shell-model calculations show a reasonable comparison with the experimental data for the yrast, positive-parity states up to spin $18\hbar$, with larger variations evident for negative-parity states with spins greater than $16\hbar$. In spite of a significant increase in angular momentum input associated with the thin target $^{76}\text{Ge}(^{18}\text{O}, p5n)$ reaction channel, as compared to the backed target data using the ^{74}Ge target, no additional discrete states were identified in the former data set, suggesting that the level scheme for this nucleus fragments significantly above the observed states, possibly indicating cross-shell excitations becoming dominant for $I > 19\hbar$.

DOI: [10.1103/PhysRevC.87.044337](https://doi.org/10.1103/PhysRevC.87.044337)

PACS number(s): 23.20.Lv, 21.60.Cs, 25.70.-z, 27.50.+e

I. INTRODUCTION

The nucleus ^{88}Y has a single neutron hole in the $N = 50$ shell and a single proton hole in the subshell at $Z = 40$. This proximity to magic and semimagic numbers suggests that the low-lying excitations for this nucleus are likely to be characterized by simple single-particle configurations that can be well described by the spherical-basis shell model. A number of previous studies have been carried out on the structure of ^{88}Y in the low-spin regime [1–5]; however, there are few investigations of the high-spin states [6]. The maximum spin that can be generated from the particles in the valence space covering the $f_{5/2}$, $p_{3/2}$, $p_{1/2}$, and $g_{9/2}$ orbitals for ^{88}Y is $24\hbar$, with higher-spin states requiring excitations across the ^{100}Sn core. A recent publication by Xu *et al.* [7] reported high-spin states of ^{88}Y populated following the heavy-ion fusion-evaporation reaction $^{82}\text{Se}(^{11}\text{B}, 5n)^{88}\text{Y}$. The level scheme for ^{88}Y presented in the current work is compared with that reported by Xu *et al.* and to the predictions of truncated basis shell-model calculations assuming excitations between the closed ^{56}Ni and ^{100}Sn doubly magic cores.

II. EXPERIMENTAL DETAILS

Heavy-ion fusion-evaporation reactions were used to produce ^{88}Y to allow the investigation of the near-yrast states up to spins of $\sim 20\hbar$. The 21-MV Extended Stretched TransUranium (ESTU) Tandem Van de Graaff accelerator at the Wright Nuclear Structure Laboratory, Yale University, produced a beam of ^{18}O which was used to create the nucleus of interest via the reactions $^{74}\text{Ge}(^{18}\text{O}, p3n)^{88}\text{Y}$ and $^{76}\text{Ge}(^{18}\text{O}, p5n)^{88}\text{Y}$. In the first experiment, a beam of ^{18}O at a laboratory energy of 60 MeV impinged a $600\text{-}\mu\text{g}/\text{cm}^2$ ^{74}Ge target with a thick ($10\text{ mg}/\text{cm}^2$) ^{197}Au backing. The second experiment, aimed at accessing higher spins, used a higher beam energy (90 MeV) on a thin ^{76}Ge target ($62\text{ }\mu\text{g}/\text{cm}^2$ on a $20\text{-}\mu\text{g}/\text{cm}^2$ carbon backing). Fusion-evaporation cross-section calculations were performed using PACE4 [8,9] to estimate the optimum beam energies for the reactions used. These calculations estimated the semiclassical maximum angular momentum input into the compound nuclei for these two reactions to be $\sim 23\hbar$ and $\sim 40\hbar$, respectively.

Discrete energy gamma rays emitted following these reactions were measured using the YRAST ball germanium detector array [10]. In the current work, the array comprised ten Compton suppressed HPGe clover detectors centered around the target chamber at a typical target-detector distance of 20 cm. The array was arranged to allow γ -ray coincidence angular correlations measurements with six clover detectors at

* Corresponding author: michael.r.bunce@gmail.com

TABLE I. Experimental details.

Beam	E_B (MeV)	Target	Backing	Beam current particle nano Amps (pNA)	Master trigger rate (kHz)	γ^3 events
^{18}O	60	^{74}Ge	^{197}Au	~ 2	~ 3	3.08×10^9
^{18}O	90	^{76}Ge	^{12}C	~ 8	~ 2	2.15×10^9

an angle of $\theta = 90^\circ$ to the beam axis and four clover detectors at $\theta = 42.5^\circ$ (two upstream and two downstream relative to the target chamber).

The hardware logic trigger for the data acquisition system was set to accept mutually coincident, independent Compton suppressed events in at least three of the ten clover detectors within a 500-ns electronic hardware time logic window. A ‘‘triples’’ clover coincidence (γ^3) master trigger was chosen to reduce system dead time and improve the overall coincidence spectral quality by ensuring that the accepted events arose from gamma-ray cascades with at least three discrete members. The data were sorted offline using the sort code CSCAN [11]. Table I provides a summary of the experimental details and number of events for each experiment in the current work.

III. RESULTS

Events corresponding to gamma rays emitted from the decay of excited nuclear states in ^{88}Y were sorted offline into two-dimensional (γ^2) matrices and three-dimensional (γ^3) coincidence cubes for investigation using the RADWARE analysis suite [12]. Figure 1 shows the total projections of the γ^2 matrices constructed from the ‘‘backed target’’ and ‘‘thin target’’ data in the current work. Previously reported gamma rays identified as originating from $^{88,89}\text{Y}$ and $^{88,89}\text{Zr}$ [13,14] are marked. The most intense of these are associated with transitions from the $4n$ evaporation channel, ^{88}Zr [14].

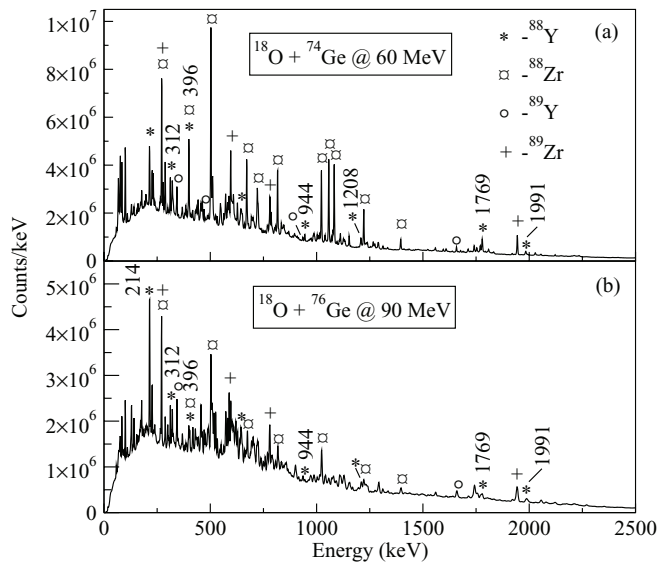


FIG. 1. Total projection of ungated symmetrized γ^2 matrices from the (a) backed target and (b) thin target experiments described in the current work.

The level scheme for ^{88}Y deduced in the current work is shown in Fig. 2 (intensities correspond to the backed target data). Coincident timing analysis techniques were used to remove random coincident events. The timing analysis involved setting various software gating conditions on time differences between measured gamma rays relative to the master trigger. A software time difference coincidence condition of ± 90 ns was applied to the γ^2 matrices as it provided the optimum

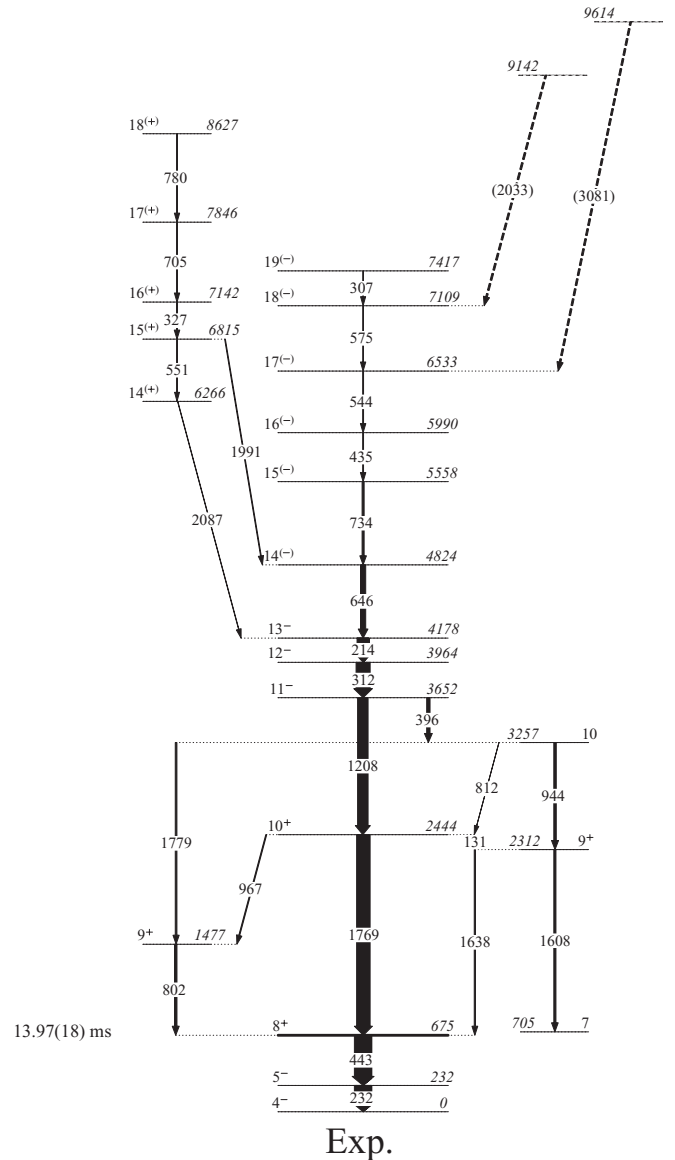


FIG. 2. Experimental level scheme for ^{88}Y constructed in the current work.

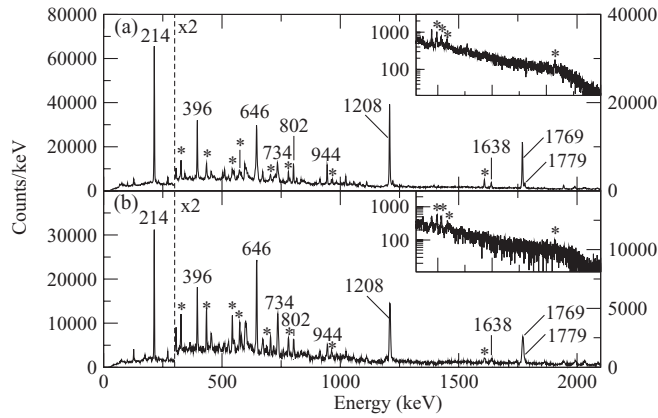


FIG. 3. Comparison of the (a) backed and (b) thin target γ^2 data with a gate set on the 312-keV transitions. Inset: x -axis range 1800–3500 keV. * indicates gamma-ray transitions associated with ^{88}Y in the current work but not reported by [6].

compromise between removal of random gamma rays and reduction in overall statistics.

The investigation of gamma-ray coincidence relationships allows for the confirmation of previously published level schemes. Figure 3 shows projections of γ^2 matrices for the backed and thin target data sets gated on the 312-keV $I^\pi = 12^- \rightarrow 11^-$ transition in ^{88}Y . Figure 4 shows the projections of the symmetrized γ^3 coincidence cube with gates on the 214- and 312-keV transitions associated with ^{88}Y , for the backed and thin target data. Notably, the relative intensity of the high-lying excitations is increased in the thin target (higher-spin-input) data as expected; however, no additional discrete energy transitions were identified in the thin target data set.

The directional correlation of oriented states (DCO) method was used to determine the likely angular momentum carried by the observed gamma rays. A $\gamma(90^\circ)\text{--}\gamma(42.5^\circ)$ coincidence matrix was constructed such that the axes corresponded to the two angular groups of detectors within the YRAST ball

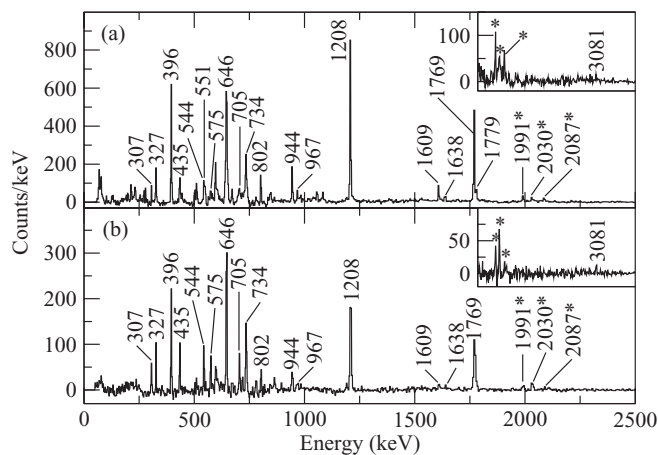


FIG. 4. Comparison of the (a) backed and (b) thin target γ^3 cube data with gates set on the 214- and 312-keV transitions. Inset: x -axis range 1800–3500 keV. Energies with * correspond to the three peaks in the inset plot.

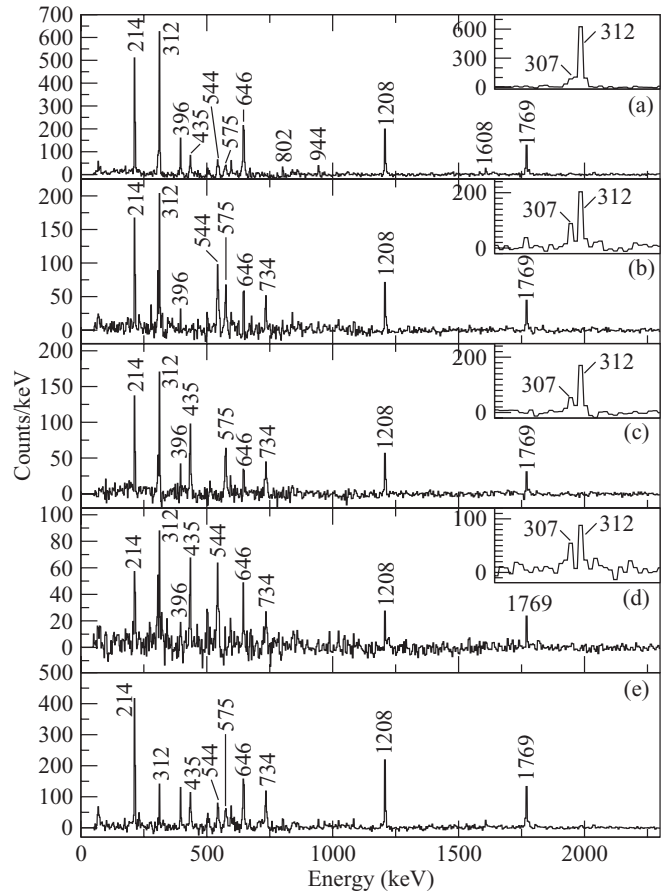


FIG. 5. Evidence for the placement of the transition at the top of the previously reported main cascade from the backed target data: sum of background subtracted, double gated projections of the symmetrized γ^3 cube with the second energy gates at 214, 312, 646, 1208, and 1769 keV with the first gate set at (a) 734 keV, (b) 435 keV, (c) 544 keV, (d) 575 keV, and (e) 307 keV. Inset: x -axis range 260–360 keV.

array. A gate with an energy corresponding to a previously reported transition of a well-defined multipolarity was then applied to both axes of this matrix. A ratio of the intensity of the projected gamma-ray peaks was measured, allowing coincident transitions with different multiplicities to be differentiated. The results of the DCO analysis of the backed and thin target data for ^{88}Y from the current work are summarized in Table II.

The current work confirms the results published by Warburton *et al.* [6] and extends the level scheme from $15\hbar$ to $19\hbar$, identifying ten additional transitions in the high-spin regime. A recent study by Xu *et al.* [7] reports many of same transitions but with a different placement to the current work. The current work places the 1608-keV transition decaying from the $E_x = 2312$ -keV $I^\pi = 9^+$ level, populating the $E_x = 705$ -keV spin-7 level. This energy is consistent with a level assigned with $I^\pi = (7^+)$ following light-ion transfer reactions in [16]. Such a state would be expected to be isomeric in nature. Xu *et al.* assigned the 1608-keV transition to populate the 5558-keV level with tentative spin and parity $I^\pi = 16^-$. Evidence for the revision of the placement of this transition in the current

TABLE II. Experimental results for ^{88}Y .

E_γ (keV)	$E_i \rightarrow E_f$ (keV)	$I_i^\pi \rightarrow I_f^\pi$ (\hbar)	$I_{\text{rel}}^{60\text{MeV}}$	$I_{\text{rel}}^{90\text{MeV}}$	$R_{\text{DCO}}^{60\text{MeV}}$		$R_{\text{DCO}}^{90\text{MeV}}$	
					1769(E2)	1208(E1)	1769(E2)	1208(E1)
131.4(10)	2444 \rightarrow 2312	10 ⁺ \rightarrow 9 ⁺	2.7(5)	3.9(15)	–	–	–	–
214.0(1)	4178 \rightarrow 3964	13 \rightarrow 12 ⁻	85(3)	115(5)	0.53(2)	0.97(7)	0.51(3)	0.96(8)
306.8(3)	7417 \rightarrow 7109	19 ⁽⁻⁾ \rightarrow 18 ⁽⁻⁾	3.7(4)	8.5(9)	–	–	0.71(17)	0.81(19)
312.1(1)	3964 \rightarrow 3652	12 \rightarrow 11 ⁻	100(3)	100(3)	0.53(3)	0.99(6)	0.52(4)	0.96(8)
327.0(10)	7142 \rightarrow 6815	16 ⁽⁺⁾ \rightarrow 15 ⁽⁺⁾	7.0(5)	12.9(11)	0.44(16)	0.87(23)	0.50(16)	1.51(36)
395.9(1)	3652 \rightarrow 3257	11 \rightarrow 10	23.9(11)	18.5(15)	–	–	–	–
434.7(2)	5990 \rightarrow 5558	16 ⁽⁻⁾ \rightarrow 15 ⁽⁻⁾	6.2(6)	16.6(15)	0.31(9)	1.03(33)	0.47(14)	0.63(11)
543.6(2)	6533 \rightarrow 5990	17 ⁽⁻⁾ \rightarrow 16 ⁽⁻⁾	6.2(5)	20.8(14)	–	–	0.59(5)	0.83(11)
550.8(2)	6815 \rightarrow 6266	15 ⁽⁺⁾ \rightarrow 14 ⁽⁺⁾	2.6(3)	3.1(6)	–	–	0.59(22)	–
575.4(3)	7109 \rightarrow 6533	18 ⁽⁻⁾ \rightarrow 17 ⁽⁻⁾	5.4(6)	19.2(16)	–	–	0.39(16)	0.71(10)
646.1(1)	4824 \rightarrow 4178	14 ⁽⁻⁾ \rightarrow 13 ⁻	37.2(14)	62(3)	0.57(9)	0.85(8)	0.46(6)	0.94(13)
704.6(2)	7846 \rightarrow 7142	17 ⁽⁺⁾ \rightarrow 16 ⁽⁺⁾	5.6(5)	12.8(15)	–	–	0.72(16)	1.18(31)
734.4(1)	5558 \rightarrow 4824	15 ⁽⁻⁾ \rightarrow 14 ⁽⁻⁾	14.5(8)	30.1(18)	–	0.88(12)	0.58(11)	0.79(10)
780.3(10)	8627 \rightarrow 7846	18 ⁽⁺⁾ \rightarrow 17 ⁽⁺⁾	5.0(24)	12.2(17)	0.36(8)	–	0.93(24)	1.32(21)
802.3(1)	1477 \rightarrow 675	9 ⁺ \rightarrow 8 ⁺	17.3(24)	12.4(17)	–	0.92(19)	–	1.01(16)
812.0(10)	3257 \rightarrow 2444	10 \rightarrow 10 ⁺	0.2(8)	0.2(7)	–	–	–	–
944.3(1)	3257 \rightarrow 2312	10 \rightarrow 9 ⁺	17.6(11)	7.5(16)	–	–	–	–
967.5(3)	2444 \rightarrow 1477	10 ⁺ \rightarrow 9 ⁺	6.6(9)	4.0(16)	–	1.46(23)	–	–
1208.2(1)	3652 \rightarrow 2444	11 \rightarrow 10 ⁺	75(3)	51.8(26)	0.54(8)	gate	0.64(7)	gate
1608.4(1)	2312 \rightarrow 704	9 ⁺ \rightarrow 7	15(2)	10.3(11)	–	–	–	–
1637.7(1)	2312 \rightarrow 675	9 ⁺ \rightarrow 8 ⁺	8.9(7)	7.9(13)	–	–	–	–
1769.3(1)	2444 \rightarrow 675	10 ⁺ \rightarrow 8 ⁺	97(4)	51(3)	gate	1.75(8)	gate	1.42(12)
1779.3(2)	3257 \rightarrow 1477	10 \rightarrow 9 ⁺	11.8(9)	7.6(16)	–	–	–	–
1991.0(2)	6815 \rightarrow 4824	15 ⁽⁺⁾ \rightarrow 14 ⁽⁻⁾	5.1(4)	8.3(9)	–	–	–	–
2032.6(10)	9142 \rightarrow 7109	–	–	–	–	–	–	–
2086.8(10)	6266 \rightarrow 4178	14 ⁽⁺⁾ \rightarrow 13 ⁻	2.2(3)	4.8(9)	–	–	–	–
3081.3(10)	9614 \rightarrow 6533	–	–	–	–	–	–	–

work is shown in Figs. 5 and 6. Figures 5(a)–5(e) (backed target data) show projections of double gated γ^3 coincidence data with the gates set on the five highest-lying transitions in the main cascade (734, 435, 544, 575, and 307 keV) as shown in Fig. 2. The absence of a discrete peak at 1608 keV indicates that this energy is not mutually coincident with these gamma

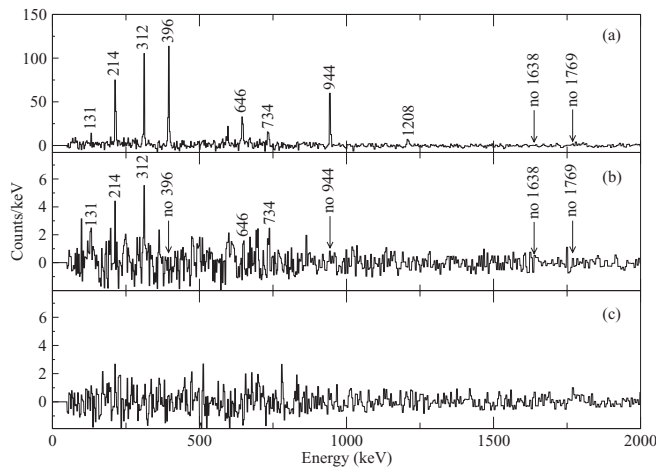


FIG. 6. Projections of double gated symmetrized γ^3 cube for the backed data. (a) Gates on 1608 and 312 plus 214 keV. (b) Gates on 1608 and 1208 keV. (c) Gates on 1608 and 1769 keV.

rays. The same conclusion is reached after analysis of the thin target data. Figure 6 shows projections of double gated γ^3 data (backed target) with the gates set on 1608 keV and a sum of 312 and 214, 1208, and 1769 keV, respectively. Figure 5(a) shows the 1608-keV γ ray to be coincident with 395 and 944 keV but not with 1638 and 1769 keV, leading to the conclusion that 1608 keV depopulates the $E_x = 2312$ -keV $I^\pi = 9^+$ level. Further support for this placement is the appearance of the weak 131-keV transition in this gate, as well as the 1208-keV peak. Figure 5(b) provides the same conclusion, with the 131-, 214-, 312-, 646-, and 734-keV transitions (but not 395 and 944 keV) present in Fig. 5(a). Figure 5(c) shows no peaks that correspond to previously reported gamma rays assigned to ^{88}Y , indicating that 1608 keV is not coincident with the 1769-keV transition. The data presented in this work also indicate that the γ ray de-exciting the 4178-keV level (214 keV) has multipolarity $\Delta I = 1$ (see Table II), which is consistent with the study of Warburton *et al.* [6]. This is contrary to the results published in [7], which assigns this transition as $\Delta I = 2$. As a result of this discrepancy, the tentatively assigned positive-parity side branch shown in Fig. 2 is consistent with the branch labeled “C” in Xu *et al.* [7] but with the member levels spins reduced by $1 \hbar$.

Two tentatively placed levels for ^{88}Y in the current work are at excitation energies of 9142 and 9614 keV. The two gamma rays depopulating these levels are seen in the inset plots of

TABLE III. Shell-model calculation results for ^{88}Y (see text for details). \dagger indicates the percentage of state wave function with this angular momentum coupling. \ddagger indicates the percentage of the total state wave function with this single-particle configuration.

State		$\%^\dagger$	Ang. mom.		$\%^\ddagger$	π occupancy			
I^π	E_x (keV)		π	ν		$f_{5/2}$	$p_{3/2}$	$p_{1/2}$	$g_{9/2}$
4 ⁻	0	81	1/2	9/2	50	6	4	1	0
					10	6	2	1	2
5 ⁻	292	88	1/2	9/2	62	6	4	1	0
					11	6	2	1	2
8 ⁺	823	88	9/2	9/2	50	6	4	0	1
					10	6	2	2	1
					10	6	2	0	3
7 ⁺	862	89	9/2	9/2	50	6	4	0	1
					10	6	2	2	1
					10	6	2	0	3
6 ⁻	1272	72	3/2	9/2	37	6	3	2	0
					16	6	3	0	2
9 ⁺	1642	89	9/2	9/2	50	6	4	0	1
					11	6	2	2	1
					10	6	2	0	3
7 ⁻	1665	93	5/2	9/2	38	5	4	2	0
					25	5	4	0	2
					13	5	2	2	2
9 ₂ ⁺	2394	23	9/2	9/2	6	6	3	1	1
					18	5	4	1	1
		60	11/2	9/2	18	6	3	1	1
					25	5	4	1	1
10 ⁺	2540	40	11/2	9/2	11	6	3	1	1
					16	5	4	1	1
		53	13/2	9/2	18	6	3	1	1
					16	5	4	1	1
8 ⁻	2991	78	7/2	9/2	43	6	3	0	2
					10	5	3	1	2
9 ⁻	3021	28	9/2	9/2	16	6	3	0	2
		60	13/2	9/2	44	6	3	0	2
10 ₂ ⁺	3319	20	11/2	9/2	9	5	4	1	1
		66	13/2	9/2	31	6	3	1	1
					23	5	4	1	1
10 ⁻	3362	85	13/2	9/2	65	6	3	0	2
11 ⁺	3439	95	13/2	9/2	32	6	3	1	1
					27	5	4	1	1
11 ⁻	3819	79	13/2	9/2	50	6	3	0	2
					7	5	4	0	2
					5	6	2	1	2
12 ⁻	4163	15	15/2	9/2	5	6	3	0	2
					6	5	4	0	2
		30	17/2	9/2	7	6	3	0	2
					13	5	4	0	2
		45	19/2	9/2	11	6	3	0	2
					23	5	4	0	2
13 ⁻	4379	40	17/2	9/2	25	5	4	0	2
		37	19/2	9/2	22	5	4	0	2
		19	21/2	9/2	13	5	4	0	2

TABLE III. (Continued.)

State		$\%^\dagger$	Ang. mom.		$\%^\ddagger$	π occupancy			
I^π	E_x (keV)		π	ν		$f_{5/2}$	$p_{3/2}$	$p_{1/2}$	$g_{9/2}$
12 ⁺	4673	63	15/2	9/2	24	5	3	2	1
					17	5	3	0	3
		30	17/2	9/2	12	5	3	2	1
14 ⁻	5074	50	19/2	9/2	30	5	4	0	2
		47	21/2	9/2	31	5	4	0	2
13 ⁺	5688	91	17/2	9/2	30	5	3	2	1
					27	5	3	0	3
					7	4	4	0	3
15 ⁻	5766	96	21/2	9/2	62	5	4	0	2
					10	5	2	2	2
					10	5	2	0	4
14 ⁺	6261	58	19/2	9/2	36	5	3	0	3
					9	4	4	0	3
		30	21/2	9/2	15	5	3	0	3
15 ⁺	6689	76	21/2	9/2	49	6	2	0	3
					7	4	4	0	3
		17	23/2	9/2	7	5	3	0	3
16 ⁻	7294	66	23/2	9/2	47	5	3	1	2
		32	25/2	9/2	23	5	3	1	2
16 ⁺	7324	67	23/2	9/2	43	5	3	0	3
					10	4	4	0	3
		22	25/2	9/2	13	5	3	0	3
17 ⁻	8108	98	25/2	9/2	67	5	3	1	2
					8	4	4	1	2
17 ⁺	8113	67	25/2	9/2	42	5	3	0	3
					11	4	4	0	3
		23	27/2	9/2	14	5	3	0	3
		9	29/2	9/2	6	5	3	0	3
18 ⁺	8847	68	27/2	9/2	42	5	3	0	3
					10	4	4	0	3
		21	29/2	9/2	19	5	3	0	3
19 ⁺	9333	97	29/2	9/2	59	5	3	0	3
					13	4	4	0	3
					7	5	2	1	3
18 ⁻	10078	63	27/2	9/2	40	5	2	0	4
					7	4	3	0	4
					7	5	1	1	4
		34	29/2	9/2	22	5	2	0	4
19 ⁻	10185	95	29/2	9/2	59	5	2	0	4
					11	4	3	0	4
					9	5	1	1	4
					6	4	2	1	4
20 ⁻	11981	96	31/2	9/2	59	5	2	0	4
					18	4	3	0	4
					6	5	1	1	4
					7	4	2	1	4
20 ⁺	12167	96	31/2	9/2	63	5	2	1	3
					26	4	3	1	3
21 ⁺	12903	100	33/2	9/2	90	4	3	1	3
21 ⁻	13357	91	33/2	9/2	44	4	3	0	4
					18	3	4	0	4
					14	4	2	1	4
		8	35/2	9/2	8	4	3	0	4

TABLE III. (*Continued.*)

I^π	State E_x (keV)	% [†]	Ang. mom.		% [‡]	π occupancy			
			π	ν		$f_{5/2}$	$p_{3/2}$	$p_{1/2}$	$g_{9/2}$
22 ⁻	13802	99	35/2	9/2	86	4	2	0	5
22 ⁺	15953	98	35/2	9/2	84	4	3	0	4
23 ⁻	16323	100	37/2	9/2	83	4	2	1	4
					15	3	3	1	4
23 ⁺	16948	100	37/2	9/2	83	4	2	0	5
					11	3	3	0	5
24 ⁺	20615	100	39/2	9/2	100	3	2	1	5

Figs. 3 and 4. Projections of the energy gates placed on these transitions in the γ^3 coincidence cube with second gates placed on the 214-, 312-, and 646-keV transitions are shown in Fig. 7. Figure 7(a) shows the 2033-keV gate with the 214-, 312-, 396-, 435-, 546-, 575-, 646-, 734-, 1208-, 1760-keV gamma rays present but not the 307-keV transition. This indicates the 2033-keV transition feeds directly into the level scheme at the $E_x = 7109$ -keV level. Figure 7(b) shows the projection of the 3081-keV gate with the 214-, 312-, 396-, 435-, 546-, 646-, 734-, 1208-, 1769-keV transitions present. The 575- and 307-keV transitions are not present in this projection, suggesting the 3081-keV gamma ray populates the $E_x = 6533$ -keV level. The parities of the previously unreported levels are assigned tentatively on the basis of comparison with the shell-model calculations discussed in the next section.

IV. SHELL-MODEL CALCULATIONS AND DISCUSSION

Truncated basis shell-model calculations were carried out for ^{88}Y using the code NUSHELLX [15]. The valence space used covered the major shell from $Z, N = 28$ –50, with a ^{56}Ni inert core. No subshell truncations were applied to this model space, allowing the valence par-

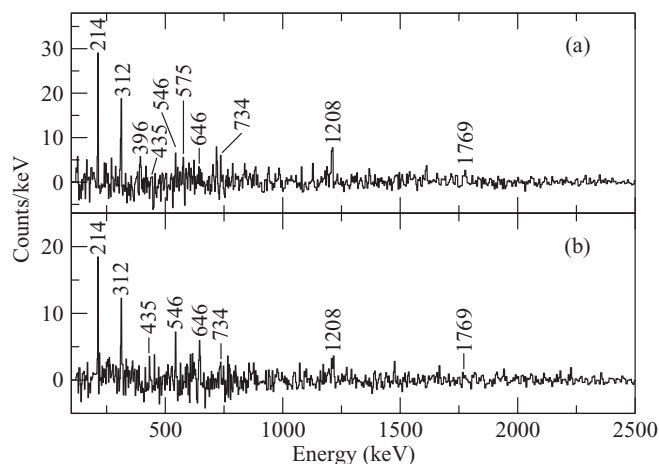


FIG. 7. Projections of background subtracted double gated γ^3 coincidences for the thin target data. (a) Sum of gates between 2033 and 214 plus 312 keV. (b) Sum of gates between 3081 and 214, 312, and 646 keV.

ticles to move freely between the $f_{5/2}$, $p_{3/2}$, $p_{1/2}$, and $g_{9/2}$ single-particle orbitals. The interaction chosen was based on the Bonn-C potential, with the four single-particle energies, $f_{5/2}$ (−8.7087 MeV), $p_{3/2}$ (−9.8280 MeV), $p_{1/2}$ (−7.8388 MeV), and $g_{9/2}$ (−6.2617 MeV), modified empirically to fit experimental energy data in the region $A = 63$ –96, including ^{89}Y (see [16]). The highest-spin and parity or highest-parity configurations possible for the valence space used in the current work are 23⁻ and 24⁺ (see Table III).

^{88}Y has one neutron hole in the $N = 28$ –50 major shell. The calculations have no subshell restrictions on the neutrons; however, it is clear from the results of these calculations that $\nu(g_{9/2})^{-1}$ is the only neutron configuration of significance. There are also no subshell restrictions placed upon the proton single-particle orbitals, allowing free movement of the 11 valence protons in the “ fp g” major shell. The results of the shell-model calculations are shown in Fig. 8, with detailed results presented in Table III. Figure 8 shows the experimental level scheme of ^{88}Y deduced in the current work alongside the shell-model calculations for ^{88}Y . The calculations for ^{88}Y show reasonable agreement with the experimental yrast level schemes up to excitation energies of ~ 5 MeV. These lower-spin and excitation yrast levels are well described by simple configurations. For example, the $I^\pi = 4^-$ and 5^- state wave functions in ^{88}Y consist of more than 80% $\pi(p_{1/2})\nu(g_{9/2})$ with other particle configurations contributing less than 5% each to the wave function. The shell-model calculation predicts the yrast $I^\pi = 8^+$ state to have an excitation energy of 823 keV. The general agreement between theory and experiment holds well, with differences of less than 200 keV, for the negative-parity states up to the $I^\pi = 15^-$, $E_x = 5766$ calculated state. Above this the difference between the theoretical and experimental results increases to more than 1 MeV, possibly suggesting competition from cross-core excitations in the formation of near-yrast states in this energy range.

As with the negative-parity states, the predicted positive-parity states show a reasonable agreement with the experimental results at lower excitation energies; however, the agreement extends to higher energies of ~ 8.6 MeV. Figure 2 shows that the predicted higher-energy positive-parity states are consistent with those states identified in a parallel side branch. If these side branch states had negative parity, i.e., the same parity as the main decay sequence, one would expect to observe competing $E2$ transitions from the $E_x = 6266$ -keV spin-14 state to the $E_x = 3964$ -keV $I^\pi = 12^-$ state and from the $E_x = 6815$ -keV spin-15 state to the $E_x = 4178$ -keV $I^\pi = 13^-$ state. The energy of such transitions would be 2302 and 2637 keV, respectively, but there is no evidence of such discrete energies in the current work, consistent with positive-parity assignments for the side branch levels.

The shell-model calculations predict that the yrast $I^\pi = 19^+$ state should be ~ 500 keV above the observed $I^\pi = 18^+$ yrast state. No firm evidence for a state corresponding to this predicted level is observed in the current work. The yrast $I^\pi = 20^+$ and 20^- states are predicted to lie almost 3 MeV above the $I^\pi = 19^+$ state (see Table III), which suggests an exhaustion of energetically favored angular momentum couplings in this valence space. The large energy gap suggests that cross-shell

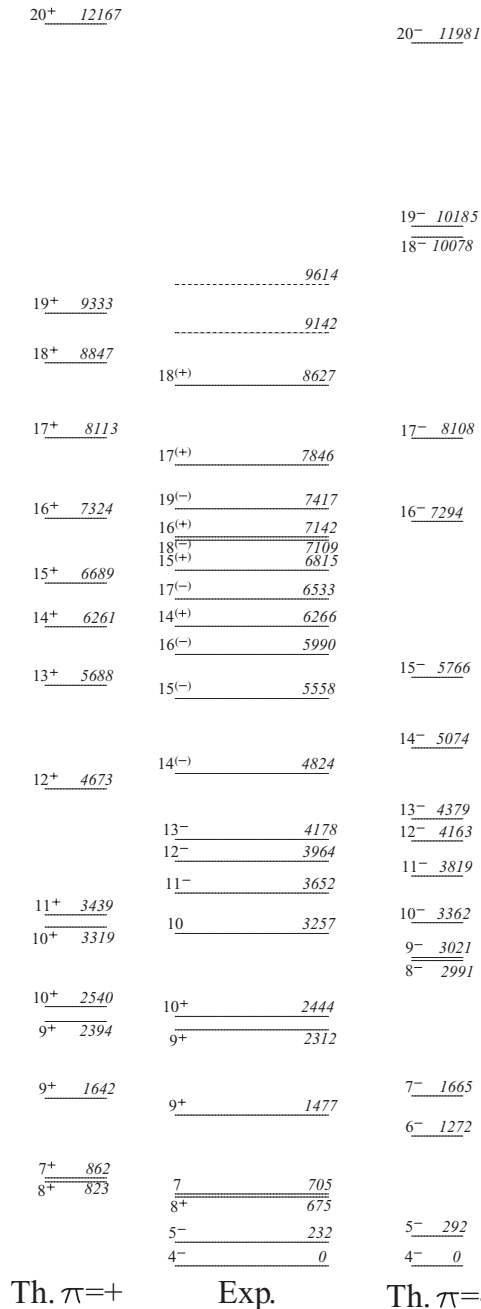


FIG. 8. Experimental level scheme for ^{88}Y constructed from the presented data alongside shell-model calculations performed using NUSHELLX and the jun45 interaction.

excitations may compete with such transitions, fragmenting the potential population of states with $I \geq 20\hbar$.

It was expected that the heavy-ion fusion-evaporation reactions would impart angular momentum up to $40\hbar$ to the nucleus under study. However, it can be seen in Fig. 2 that the extended experimental level scheme for ^{88}Y only exhibits levels up to a spin of $19\hbar$. It is possible that no discrete levels are observed at higher spins in the current work due to the level scheme fragmenting, with a large number of weakly populated levels that are difficult to observe discretely.

Above ~ 5 MeV the agreement between experiment and theoretical prediction becomes weaker. At some stage, the excitation energy will become sufficient for a neutron excitation across the $N = 50$ shell gap. The $N = 50$ shell gap is of the order of several MeV, meaning that within the energy range being examined it is possible for neutrons to excite across the gap. However, the calculation model space used includes only single-particle states up to $g_{9/2}$ for both protons and neutrons, therefore allowing no excitations across the $N = 50$ shell gap. This is likely to be the source of the large differences between the shell-model calculations and the experimental levels scheme at high excitation energies.

V. CONCLUSIONS

A spectroscopic study of the near-magic, odd-odd nucleus ^{88}Y has been performed. Previously unreported data have been used to present a level scheme that extends to higher excitation energy and spin than previously reported. Angular correlation measurements were performed, allowing the confirmation of previously reported level angular momentum and newly observed level angular momentum to be assigned. Shell-model calculations were performed using NUSHELLX, and reasonable agreement between experimental data and theoretical predications was achieved for states with $I \leq 18\hbar$. No evidence for decays from discrete levels with $I \geq 20\hbar$ was observed in the current work, in spite of a semiclassical angular momentum of $>40\hbar$ being imparted. This suggests a complex fragmentation of the level scheme for ^{88}Y above $I \geq 18\hbar$ associated with excitations across the $N = 50$ closed shell.

ACKNOWLEDGMENTS

The author would like to acknowledge the excellent work of all the technical staff at the Wright Nuclear Structure Laboratory. This work is supported by Science and Technology Facilities Council (STFC), United Kingdom, under Grant No. EP/D077133/1, and the U.S. Department of Energy under Grants No. DE-FG02-91ER40609, No. DE-FG52-06NA26206, and No. DE-FG02-05ER41379.

- [1] F. Gabbard, G. Chenevert, and K. K. Sekharan, *Phys. Rev. C* **6**, 2167 (1972).
 [2] M. Davidson, J. Davidson, and M. A. J. Mariscotti, *Nucl. Phys. A* **352**, 237 (1981).
 [3] H. W. Baer *et al.*, *Nucl. Phys. A* **218**, 355 (1974).

- [4] J. R. Comfort and J. P. Schiffer, *Phys. Rev. C* **4**, 803 (1971).
 [5] J. L. Horton and C. E. Hollandsworth, *Phys. Rev. C* **13**, 2212 (1976).
 [6] E. K. Warburton *et al.*, *J. Phys. G* **12**, 1017 (1986).

- [7] C. J. Xu *et al.*, *Phys. Rev. C* **86**, 027302 (2012).
- [8] O. B. Tarasov and D. Bazin, *Nucl. Instrum. Meth. A* **204**, 174 (2003).
- [9] A. Gavron, *Phys. Rev. C* **21**, 230 (1980).
- [10] C. W. Beausang *et al.*, *Nucl. Instr. and Meth. A* **452**, 431 (2000).
- [11] M. A. Caprio and J. J. Ressler (unpublished).
- [12] D. C. Radford, *Nucl. Instrum. Meth. A* **361**, 297 (1995).
- [13] G. Mukherjee and A. A. Sonzogni, *Nucl. Data Sheets* **105**, 419 (2005).
- [14] B. Singh, *Nuclear Data Sheets* **85**, 1 (1998).
- [15] B. A. Brown and W. D. M. Rae, MSU-NSCL Report No. XX, 2007 (unpublished).
- [16] M. Honma, T. Otsuka, T. Mizusaki, and M. Hjorth-Jensen, *Phys. Rev. C* **80**, 064323 (2009).