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Unveiling New States in ^{98}Zr: Insights from β-decay and γ-γ Angular-Correlation Studies

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Abstract. The nuclear structure of the ^{98}Zr nucleus was studied through the β^- decay of $^{98}Y_{g.s.}$ at the TRIUMF-ISAC facility. The use of the 8π γ-ray spectrometer with its ancillary detectors SCEPTAR and PACES enabled γ-γ and γ-e^- coincidence measurements as well as γ-γ angular correlations. The level spin assignments and transition mixing ratios obtained in this study were in good agreement with previous results. Furthermore, 12 previously unknown states in the low-energy region of ^{98}Zr were identified, including the 0^+_5 and 0^+_6 levels at 2418 and 2749 keV, respectively. The 2^+ and $I = 1$ natures for multiple newly observed and previously known (but not firmly assigned) states have been established. Additionally, the previously assumed pure $E2$ character of the $2^+_2 \rightarrow 2^+_1$ 367.8-keV transition was confirmed.

1 Introduction

Anomalies in the systematics of nuclear properties pose challenges to our understanding of the underlying nuclear structure. One such anomaly emerges in the Zr isotopic chain where a dramatic ground-state shape change occurs, abruptly shifting from spherical into a deformed one at N=60. Only a select number of advanced theoretical models have been successful in reproducing this deformation onset in ^{100}Zr, which helped to establish the shape coexistence in lighter Zr isotopes [1, 2]. Of particular interest is ^{98}Zr, a transitional nucleus lying on the interface between spherical and deformed phases. Extensive experimental and theoretical studies have been performed investigating the shape coexistence phenomena in this isotope [3–6], but considerable uncertainties remain in interpreting the nature of its states. Specifically, two recent experimental studies supported by Monte Carlo Shell Model (MCSM) [3] and Interacting Boson Model with configuration mixing (IBM-CM) [4] calculations have presented conflicting interpretations. The MCSM predicts multiple shape coexistence with deformed band structures, whereas the IBM-CM favours a multiphonon-like structures with configuration mixing.

In order to investigate the structure of ^{98}Zr, a β-decay experiment was conducted utilizing the 8π γ-ray spectrometer. The high-quality and high-statistics data obtained enabled the observation of low-energy transitions from levels at high excitation energy. The firm placement and measurements of branching ratios for these weak transitions are crucial for assigning band structures. Additionally, γ-γ angular correlation measurements enabled both spin assignments and mixing ratio determinations. While the γ-ray coincidence analysis is in its final stages with definitive results planned for a subsequent publication, this work primarily emphasizes the angular correlation measurements performed for ^{98}Zr states below 3.4 MeV.

2 Experimental Details

The β-decay experiment was conducted at the TRIUMF-ISAC facility. The isotopes of interest were produced through the 500-MeV proton-induced spallation and fission reactions of a UC_x target. The reaction products diffused through the target and were ionized to the 1^+ charge state by a Re surface ion source, after which the

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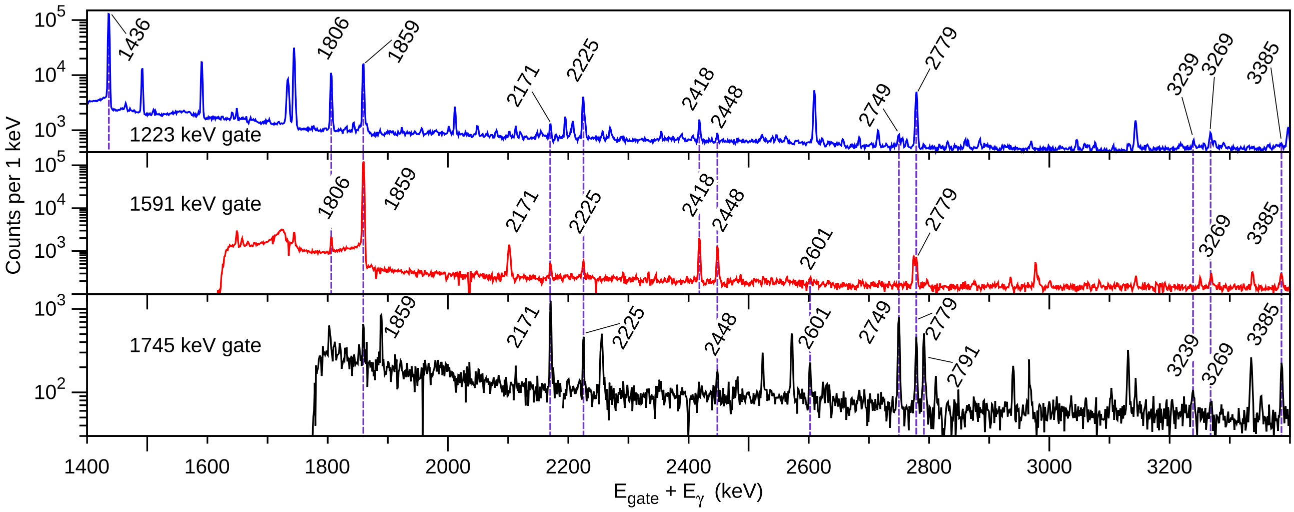

Figure 1. (Color online) Partial γ-ray energy spectra in coincidence with the 1223- (blue), 1591- (red), and 1745-keV (black) $2^+ \rightarrow 0^+_{g.s.}$ transitions. The gated spectra are shifted by their respective energies to align the coincident γ-ray peaks with the energies of states that they de-excite from. γ-ray transitions branching from levels in ^{98}Zr are labeled and indicated by the dashed lines.

beam passed through a magnetic separator with a resolution of $\Delta M/M \approx 1/1000$. While the β^- decay of ^{98}Y ($T_{1/2}$ = 548(2) ms) to ^{98}Zr ($T_{1/2}$ = 30.7(4) s) was the main focus of this work, the refractory nature of Y made it challenging to extract ^{98}Y ions directly. Therefore, the separator was tuned to optimize the selection of A=98 Rb and Sr ions that were accelerated to 30 keV and delivered to the experimental station. The beam was deposited onto a movable FeO-coated mylar tape, where the decays of ^{98}Rb ($T_{1/2}$ = 102(4) ms) and ^{98}Sr ($T_{1/2}$ = 653(2) ms) were used to build a source of ^{98}Y. Given the low ground-state spin-parity configurations of the parent nuclei in this decay chain, the $^{98}Y^m$ ($J^\pi = (4,5)$) isomer was not populated. Moreover, the tape movement cycles were optimized to maximize the β-decay activity of ^{98}Y and minimize the activity of other decay products. The beam implantation site was surrounded by 20 Compton-suppressed, hyper-pure germanium (HPGe) detectors of the 8π array [7] which enabled γ-singles and γ-γ coincidence measurements. The physical geometry of the 8π array is such that detectors are grouped based on their angular orientation resulting in five distinct correlation angles. This arrangement facilitated angular correlation measurements which are further discussed in section 3.2. Additionally, two auxiliary detectors were employed in the experiment, SCEPTAR and PACES [8], which enabled both β-tagging and internal conversion electron spectroscopy capabilities, respectively. Standard ^{152}Eu, ^{133}Ba, ^{60}Co, and ^{56}Co sources were used in order to perform energy and efficiency calibrations of the 8π HPGe array, while the PACES relative efficiency curve was determined utilising the in-beam γ-e^- data of transitions with well-known multipolarities.

3 Results and Discussion

The experimental data were processed and sorted offline using the *gsort* code developed by the Nuclear Physics Group at the University of Guelph. The resultant Compton-suppressed and time-random subtracted γ-γ and γ-e^- coincidence matrices contained $3.2 \cdot 10^8$ and $2.3 \cdot 10^8$ events, respectively, with approximately 10^9 events recorded in the γ-singles regime. Furthermore, a matrix of E_γ *vs.* event time in the cycle was constructed, which enabled differentiation between γ-ray transitions emitted from species with varying half-lives. This procedure also allowed the selection of event times for the γ-γ coincidence data to optimize the selection of the ^{98}Sr and ^{98}Y decay events due to the longer half-life compared with ^{98}Rb. Finally, the sorted data were analyzed with the `HDTV` [9] and `RADWARE` [10] software packages.

3.1 Coincidence Analysis

In order to identify the states populated in the β decay of $^{98}Y_{g.s.}$, a set of γ-coincidence gates were placed on intense transitions depopulating from lower-lying states in ^{98}Zr. The projected spectra were then shifted by the respective level excitation energies, so that the peaks from the coincident feeding transitions aligned with the energy of the state from which they de-excited. By overlaying the energy-shifted spectra, as shown in Fig. 1, transitions originating from the same level could be easily identified. In the present γ-γ coincidence analysis, gates were set on the ground-state transitions depopulating the $2^+_1, 2^+_2$, and 2^+_3 levels at energies 1223, 1591, and 1745 keV. Furthermore, gates were also set on the 215- ($0^+_3 \rightarrow 2^+_2$), 583- ($3^-_1 \rightarrow 2^+_2$), and 269-keV ($0^+_4 \rightarrow 2^+_3$) transitions, which decay from the 1436 keV, 1806 keV, and 1859 keV states, respectively. The γ-e^- coincidences were also utilized to gate on the 854-keV $0^+_2 \rightarrow 0^+_1$ $E0$ transition. By combining this approach with further γ-γ coincidence and γ-ray singles analysis, 35 previously unknown levels up to 5.6 MeV were identified in the β^- decay of ^{98}Y, greatly expanding the known level scheme of ^{98}Zr. All identified states up to 3.4 MeV, along with their corresponding energies and spin assignments, are summarized in Tab. 1, together with the results of the angular-correlation analysis, which are further discussed in the following subsection.

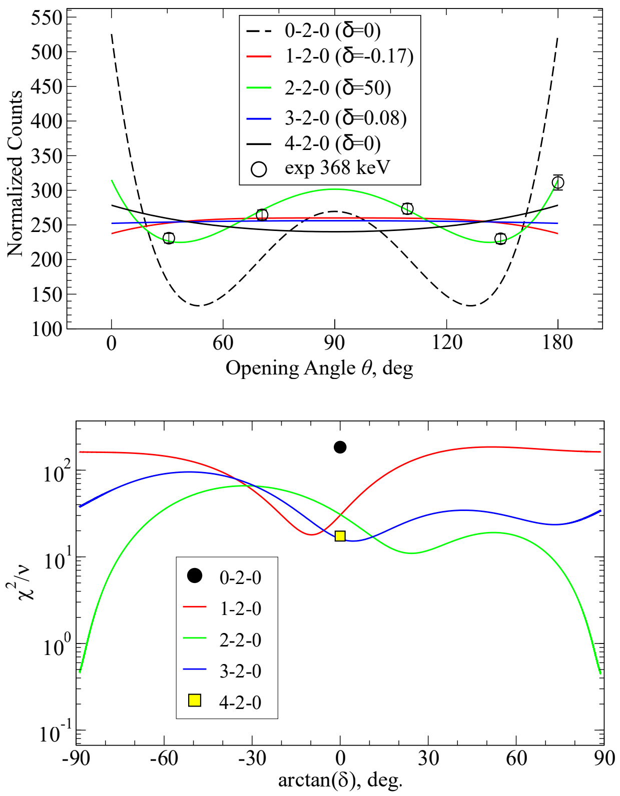

Figure 2. (Color online) The γ-γ angular correlation data obtained for the 367.8-keV and 1222.9-keV cascade (top panel) together with the corresponding reduced χ^2 curves (bottom panel). The χ^2 curves are plotted as function of the mixing ratio δ for the different spin hypotheses for 1591-keV level, which are indicated in the figure legends.

3.2 Angular Correlations

The geometry of the 8π array allows for pairing the 20 HPGe detectors into five unique correlation angles: 41.8, 70.5, 109.5, 138.2, and 180 degrees. Due to the exclusion of one malfunctioning HPGe detector in the analysis, the numbers of detector-pair combinations for each angle were calculated to be 27, 54, 54, 27, 9, respectively. Angular-correlation analysis using this setup excels at identifying 0^+ states, thanks to the distinct shape of the 0-2-0 angular distribution and its apparent enhancement at 180 degrees. However, as with many angular correlation analyses, it becomes difficult to differentiate between similar angular distributions of certain non-0^+ states. A particular disadvantage of the 8π spectrometer is the low number of detector pairs constituting the 180-degree angle that limits the statistics in the respective correlation angle γ-γ matrix, allowing only the analysis of high-intensity γ-ray cascades. Based on the above considerations, the strong 1222.9-, 1590.8-, and 1744.5-keV $2^+ \rightarrow 0^+$ transitions were taken as the reference for stretched quadrupole transitions in the present angular-correlation study. The level spin assignments were determined by fitting the experimentally measured angular distributions to the theoretical angular correlation functions using the χ^2 minimization technique. The mixing ratio (δ) was also used as a fit parameter for transitions of mixed multipolarity and the values of δ that minimized the χ^2 were extracted. The interested reader is referred to Refs. [11, 12] for more detailed explanations of the γ-γ angular correlations performed with the 8π spectrometer.

The results of the angular-correlation analysis are presented in Tab. 1, showing the spin assignments of levels populated in ^{98}Zr as well as the δ mixing ratios for the corresponding γ-ray transitions. In instances where the minimized χ^2 indicated valid solutions for multiple spins, the associated spin cascades and mixing ratios were listed in ascending order of their minimized χ^2 values. Furthermore, unlikely spin solutions were ruled out by examining the final (or initial) states of transitions decaying out of (or feeding into) the levels of interest and by invoking the γ-decay selection rules.

The present angular-correlation study not only confirmed prior spin assignments reported in Ref. [13], but also solidified tentative spin assignments and established spins for 6 newly-observed states. Notably, two previously unknown states at 2418 and 2749 keV were identified to be the 0^+_5 and 0^+_6 states, which is of great significance for interpreting the nuclear structure of ^{98}Zr. Furthermore, the mixing ratios deduced in this study align closely with literature values reported in Ref. [14]. For instance, the mixing ratio for the $2^+_3 \rightarrow 2^+_1$ 521.6-keV transition was previously measured to be 0.44(4), whereas in this work a value of 0.42(5) was obtained. Transitions characterized as pure electric quadrupole have been denoted as $E2$ in Tab. 1. Beyond the $0 \rightarrow 2 \rightarrow 0$ cascades, the 367.8-keV transition from the 2^+_2 state at 1591 keV to the 2^+_1 level at 1223 keV was also identified as being predominately $E2$ in nature. The γ-γ angular correlation data of this transition is shown in Fig. 2 together with the χ^2 curves for the corresponding spin cascades. The minimization of χ^2 clearly indicates that the $2^+_2 \rightarrow 2^+_1$ transition is dominated by the $E2$ component. This result firmly establishes the collective nature of this transition based on the large $B(E2)$ value of 46^{+35}_{-14} W.u. reported in Ref. [4]. The tentative $J^\pi = 2^+$ assignments for states at 2225 and 2779 keV were confirmed in the present study, while additional level of 2^+ character was also firmly established at 2448 keV. The 0^- ground-state configuration of ^{98}Y and the high Q_β value of 8992(12) keV indicate that the levels of a primarily 1^- nature are populated above 3.4 MeV in ^{98}Zr. This is further supported by previous β-decay studies on high-energy levels in ^{96}Zr [15, 16], where it is observed that the Pygmy Dipole Resonance plays a significant role in the enhanced population of the high-energy 1^- states.

4 Conclusions

The level structure of ^{98}Zr has been investigated via the β^- decay of ^{98}Y$_{\text{g.s.}}$ ($J^\pi = 0^-$) at the TRIUMF-ISAC facility

Table 1. Level energies, spin assignments, and mixing ratios (δ) of γ-ray transitions in ^{98}Zr, populated in the β decay of $^{98}Y_{g.s.}$. The table is divided into sections according to the reference E2 transitions used for γ-γ angular correlations. A separate section includes levels identified through γ-singles and coincidence analysis. Values of J^π_{lit} are taken from Ref. [13].

Initial Level			γ decay	Spins	$\delta_{new}(\gamma_1)$
E_i (keV)	J^π_{lit}	J^π_{new}	γ_1 (keV)	I_1, I_2, I_3	
		$\gamma_1 \longrightarrow 1222.9 \longrightarrow 0.0$			
1436	0^+	0^+	213.2	$0\to2\to0$	E2
1591	2^+	2^+	367.8	$2\to2\to0$	E2
1745	2^+	2^+	521.6	$2\to2\to0$	$0.42^{+0.05}_{-0.05}$
1806	3^-	3^-	583.2	$3\to2\to0$	$0.01^{+0.04}_{-0.05}$
				$2\to2\to0$	$0.44^{+0.06}_{-0.06}$
				$1\to2\to0$	$-0.16^{+0.03}_{-0.04}$
1859	0^+	0^+	636.5	$0\to2\to0$	E2
2171 [A]		$(1,2^+)$	947.0	$2\to2\to0$	$0.73^{+0.62}_{-0.25}$
				$1\to2\to0$	$-0.05^{+0.10}_{-0.09}$
2225	(2^+)	2^+	1002.3	$2\to2\to0$	$-1.48^{+0.24}_{-0.25}$
2418 [A]		0^+	1194.7	$0\to2\to0$	E2
2779	(2^+)	2^+	1555.7	$2\to2\to0$	$-0.09^{+0.06}_{-0.06}$
3267 [A]		(1)	2044.5	$1\to2\to0$	26^{+24}_{-19}
3274 [A]		(1,2)	2051.7	$1\to2\to0$	$-2.6^{+1.9}_{-6.4}$
				$2\to2\to0$	$-0.12^{+0.23}_{-0.31}$
		$\gamma_1 \longrightarrow 1590.8 \longrightarrow 0.0$			
1745	2^+	2^+	152.7	$2\to2\to0$	$-0.08^{+0.14}_{-0.16}$
1859	0^+	0^+	268.7	$0\to2\to0$	E2
2171 [A]		$(1,2^+)$	580.1	$2\to2\to0$	$-3.8^{+1.8}_{-14}$
				$1\to2\to0$	$-0.27^{+0.13}_{-0.15}$
2418 [A]		0^+	827.1	$0\to2\to0$	E2
2448 [A]		2^+	857.1	$2\to2\to0$	$-4.9^{+1.4}_{-3.0}$
2779	(2^+)	2^+	1187.8	$2\to2\to0$	$-2.5^{+0.7}_{-1.2}$
3385 [A]		(1,2)	1794.0	$2\to2\to0$	$-0.93^{+0.57}_{-0.63}$
				$1\to2\to0$	$-0.27^{+0.13}_{-0.15}$
		$\gamma_1 \longrightarrow 1744.5 \longrightarrow 0.0$			
2225	(2^+)	2^+	481.0	$2\to2\to0$	$-0.35^{+0.22}_{-0.60}$
2602 [A]		(1)	857.4	$1\to2\to0$	$-4.2^{+2.2}_{-16}$
2749 [A]		0^+	1004.7	$0\to2\to0$	E2
2779	(2^+)	2^+	1033.8	$2\to2\to0$	$-0.35^{+0.22}_{-1.07}$
2791 [A]		(1,2)	1046.4	$2\to2\to0$	$-0.27^{+3.5}_{-0.36}$
				$1\to2\to0$	$-0.69^{+0.12}_{-0.15}$
3385 [A]		(1,2)	1641.0	$1\to2\to0$	$-0.3^{+4.0}_{-9.3}$
				$2\to2\to0$	$0.2^{+5.2}_{-0.4}$
		Other Populated Levels			
2775 [A]		(1) [B]			
2859 [A]		$(1^-, 2^+)$ [B]			
3066	(1)	(1) [B]			
3239 [A]		(1, 2) [B]			

[A] Level identified in this work.
[B] J^π assignment based on γ-decay selection rules.

using the 8π spectrometer. The acquired data were analyzed utilizing γ-singles, γ-γ, and γ-e^- coincidence techniques, in addition to the γ-γ angular correlation method. In this study, the results were found to be in good agreement with the previous spin assignments and mixing ratio values reported in the literature. Thus far, 12 new states in ^{98}Zr have been identified in the energy region up to 3.4 MeV. Among these, the levels at 2418 and 2749 keV have been assigned as 0^+_5 and 0^+_6, respectively. The predominant $E2$ nature of the $2^+_2 \to 2^+_1$ 367.8-keV transition validated the collective character of the 2^+_2 state. Additionally, a 2^+ spin-parity configuration has been firmly established for four more states below 3 MeV. The analysis of γ-γ coincidence data is nearing completion and results on the branching ratios, B(E2) values, band assignments and higher energy levels will be reported in a subsequent publication.

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