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Abstract

The low-spin β-decay of ^{96,98}Y has been reinvestigated to obtain detailed information on the fast first-forbidden transitions to the ground states of ^{96,98}Zr. A considerably more detailed decay scheme of ^{96}Y confirms the general features of a previous study. The spin of the ground state of ^{98}Y has been measured to be 0^- from $\gamma\gamma(\Theta)$ angular correlations in ^{98}Sr$\rightarrow^{98}$Y decay and from Q_β measurements by $\beta-\gamma$ coincidences in the decay of ^{98}Y$\rightarrow^{98}$Zr. From β-decay data on $^{90-100}$Y nuclei, mixing of the "spherical" and "collective" 0^+ states is deduced, and the strength of the mixing matrix elements is found to vary greatly across the Zr nuclei.

Introduction

One of the unique features of the A=100 region is the existence of a nearly doubly magic ^{96}Zr nucleus in close vicinity to deformed heavier Zr nuclei. Strong subshell closures at Z=40 and N=56 are manifested [1] by a high-lying 2_1^+ state at 1750 keV and by the purity of the 0^+ ground state (g.s.) configuration. A previous study [1] clarified the existence of a fast first-forbidden $0^-\rightarrow0^+$ β transition in the decay of ^{96}Y.

Fast $0^-\rightarrow0^+$ first-forbidden β transitions have been observed [1-3] in the vicinity of doubly-closed shell nuclei such as ^{16}O, ^{96}Zr, and ^{208}Pb, and attributed to the $\nu s_{1/2}\rightarrow\pi p_{1/2}$ transition. The purity of the shell model configurations and the high overlap between the configurations involved provide enhancement [4] of the decay rates over typical limits [5]. Further enhancement is caused by meson-exchange effects [6]. In fact, shell model calculations based on the data from Ref. 1 indicate a ~70% enhancement of the ^{96}Y decay rate due to meson-exchange effects [6].

The study of Ref. 1 did not elucidate the β feeding to high-lying levels in ^{96}Zr or high energy γ transitions feeding the g.s. Although this feeding is generally weak and does not significantly alter logft values deduced for low-lying levels, evidence of strongly β-fed (~50%) 1^- levels at excitation energies of ~4.2 MeV has been reported [7] for the decay of ^{98}Y$\rightarrow^{98}$Zr. Thus the possibility that the decay of 0^- $^{96}Y \rightarrow ^{96}Zr$ has similar features is opened. Motivated by the importance of a correct decay scheme to the study of meson-exchange effects we have reinvestigated the low-spin β decay of ^{96}Y in order to clarify the β feeding to the high-lying levels and to confirm other quantities pertinent to the assignment of $\log ft$ values. We have also clarified the spin assignment of the ^{98}Y g.s. which feeds the 0^+ g.s. of ^{98}Zr by a rather fast first-forbidden β transition [7].

The experiments were performed at the TRISTAN fission product mass separator at BNL. Details of the experimental procedures will be published elsewhere [8]. We have measured γ singles, γ-multispectral scaling, and $\gamma-\gamma$ and $e^- - \gamma$ coincidences in the decay of the 0^- ^{96}Y isomer. For A=96,98 nuclei Q_β was measured using a $\beta-\gamma$ coincidence technique and absolute E0 and γ-ray intensities were obtained from singles conversion electron and γ spectra measured at beam saturation. The $\gamma\gamma(\Theta)$ angular correlation experiments for the decay of $^{98}Sr \rightarrow ^{98}Y$ were performed using a four-detector system [9] which allowed simultaneous measurements at angles of 90°, 105°, 120°, 135°, 150°, and 165°.

$^{96}Y \rightarrow ^{96}Zr$

Our more precise measurements of this decay confirm the findings of Ref. 1. Although 35 new levels were found at the excitation energies from 3.5 to 6.5 MeV, their total β feeding is only ~0.5%. The new decay scheme will not be presented here. It is sufficient to note for the present purpose that no new energy levels are found below 3.0 MeV and that the new values for the half-life of 5.34(5) s, Q_β=7.07(3) MeV and the g.s. β feeding of 95.5(5)% for $^{96}Y \rightarrow ^{96}Zr$ compare well with the previous values [1,10] of 5.4(1) s, 7.14(4) MeV and 95.2(9)%. The important β feeding [1] of the 0^+ 1581-keV level is confirmed to be 1.2(2)% in agreement with the value of 1.3(5)% reported previously [1]. The β feeding to the 2^+ state at 1750 keV was found to be 1.9(3)% which is slightly lower than the previously obtained [1] value of 2.4(9)%. Absolute intensities of the E0 and γ-ray transitions reported [1,7] for the A=96 and 98 mass chains are confirmed. In particular, the absolute intensity of the 1581-keV E0 transition in ^{96}Zr was found to be 1.40(15)% in agreement with the value of 1.4(5)% of Ref. 1.

$^{98}Y \rightarrow ^{98}Zr$.

Similar to the decay of ^{96}Y, the decay of ^{98}Y has been found [7] to proceed via a rather fast first-forbidden β transition to the g.s. of ^{98}Zr, $\log ft$=5.8. The negative parity of the g.s. of ^{98}Y depends [7] on the $J^\pi=1^+$ assignments for the 547 and 600-keV levels in this nucleus. These assignments were deduced [7] from $\log ft$ values of 4.7 and 4.3, respectively, observed in the β decay of the 0^+ g.s. of ^{98}Sr and electron conversion coefficients for the γ transitions deexciting these 1^+ levels and feeding the g.s. New conversion coefficients of α_K=0.08(2), 0.0017(3), 0.0037(4), 0.0013(8), and 0.0025(7) for the 119, 428, 444, 481 and 564-keV γ rays in ^{98}Y support the multipolarity assignments used in Ref. 7.

The spin J=1 was assigned [7] for the g.s. of ^{98}Y based on β-decay rates of logft~6 to the known 0^+ and 2^+ levels in ^{98}Zr that were deduced from the absolute E0 and γ-ray intensities of Ref. 7 and the decay scheme of Ref. 11. A fast first-forbidden β transition [7], logft=5.8, between the ground states of ^{98}Y and ^{98}Zr implies [4] rather pure shell model configurations for these states. $J^\pi=1^-$ can be formed in the ^{98}Y g.s. by coupling either the $s_{1/2}$ or $d_{3/2}$ neutron to a valence $p_{1/2}$ proton. However, the parabolic rule suggests [12] the g.s. is 0^- for $\nu s_{1/2}$ or 2^- for $\nu d_{3/2}$ coupling.

The angular correlation data rule out the J=1 assignment for the ^{98}Y g.s. but support either a J=0 or 2 value. The 428−119 keV γ cascade in ^{98}Y has a_2=−0.33(5) and a_4=0.09(8) and is consistent with a_2=−0.23(6) and a_4=0.07(10) measured by Becker [13]. The correlation data were fitted to various spin sequences (see Fig. 1) restricted by $J^\pi=1^+$ for the 547-keV level and δ(L+1/L)-mixing ratios allowed by the internal conversion coefficients listed above. Two spin sequences, $1\rightarrow1\rightarrow0$ and $1\rightarrow2\rightarrow2$, were found to be consistent with the data and give $J^\pi=0^-$ or 2^- for the g.s. of ^{98}Y. This assignment is in conflict with the apparent strong β feeding, logft~6, to levels of spin 0^+ and 2^+ in ^{98}Zr [7,11]. This issue was resolved by the Q_β measurements.

Table 1 presents results from Q_β measurements by $\beta-\gamma$ coincidences for three groups of levels in ^{98}Zr. In the first group, which consists of high-lying levels ($E_x \geq$4.0 MeV), β-feeding energies, E_β, provide a Q_β value of 8963(41) keV which is consistent with the adopted value of Q_β=8890(70) keV [10]. Similar Q_β values are deduced for the group of 0^+ levels and confirm direct β-feeding to these levels. However, the Q_β values for the group of 2^+ levels are lower than the accepted Q_β energy and show no consistent pattern. The values imply an indirect β feeding to these levels while the lack of a pattern rules out the possibility of a second isomer in ^{98}Y. The decay scheme of Ref. 11 is thus incomplete. Strong β feeding to the 0^+ states in ^{98}Zr and weak feeding to the 2^+ levels rules out $J^\pi=2^-$ for the g.s. of ^{98}Y but supports the 0^- spin assignment.

Mixing matrix elements for 0_1^+ and 0_2^+ states in even-even Zr nuclei

The mixing of the 0^+ g.s. and the low-lying 0^+ intruder state has been previously deduced for $^{90-94}$Zr from particle transfer reaction data [14] under the assumption that the dominant proton component of the 0_2^+ states in Zr arises from a proton pair excitation across the Z=40 subshell gap from the $\pi p_{1/2}$ to the $\pi g_{9/2}$ orbit. The g.s. and 0_2^+ states are assumed to have admixed wave functions $\Psi_{gs}=A\varphi_1+B\varphi_2$ and $\Psi_{0_2^+}=-B\varphi_1+A\varphi_2$, where φ_1 has a $(\pi p_{1/2})^2$ and φ_2 a $(\pi g_{9/2})^2$ configuration. The mixing of these states can also be deduced from the β^- decay of Y→Zr nuclei [1,7]. Since the β-decay matrix element connecting the odd $d_{5/2}$ neutron in $^{90-94}$Y (and $s_{1/2}$ neutron in ^{96,98}Y) with a $p_{1/2}$ proton is large, while the transition to a $g_{9/2}$ proton is highly hindered, the β feeding of the 0_2^+ state is attributed to admixtures of the g.s. configuration. Consequently, from the ratio of the comparative half-lives, which is approximately equal to the square of the amount of mixing, one can deduce the B^2 value for these levels. Table 2 (columns 3 and 5) gives B^2 values deduced from particle transfer [14] and β-decay data [1,7,16], respectively. In columns 4 and 6 the strength of the mixing matrix element, $M=(\varphi_1 \mid V \mid \varphi_2)$, is deduced assuming two-level mixing and using the data in columns 2, 3 and 5, respectively.

Table 2 illustrates two characteristic features of the heavy Zr nuclei: a) the mixing amplitude of the 0_1^+ and 0_2^+ states, B^2, shows a sharp minimum at N=56, where it has a much lower value than at N=50, and b) the value of the mixing matrix element, M, is gradually reduced with increased neutron number (there may be a slight increase for N=58) and shows a sudden drop at N=60. In comparison to ^{90}Zr, the very low mixing amplitude in ^{96}Zr arises from the much lower mixing matrix element; while in comparison to the N=52-60 nuclei, it is mainly due to the higher 0_2^+ excitation energy in ^{96}Zr which reflects the strong subshell closure at Z=40 and N=56. The striking difference observed [1] in the mixing amplitudes for two otherwise similar nuclei, ^{90}Zr and ^{96}Zr, can now be explained by following the argument of Heyde *et al.* [17] discussed next.

Heyde *et al.* [17] have pointed out that a large reduction in the mixing matrix element connecting the 0_1^+ and 0_2^+ states is needed (from ~800 keV at N=50 to ~200 keV at N=60) to explain the very low 0_2^+ excitation energy in ^{98,100}Zr. This reduction has been calculated [17] as arising from a diminished overlap between spherical and Nilsson model deformed neutron wave functions, which describe the neutron component in spherical and collective (intruder) configurations, respectively. As deformation sets in the configuration mixing characterizing the Nilsson wave functions reduces their overlap with spherical shell model configurations.

Discussion

The present study confirmed the general features of the decay of the 0^- isomer of ^{96}Y reported in Ref. 1 including the logft=5.6 for the crucial $0^- \rightarrow 0^+$ fast first-forbidden β transition to g.s. of ^{96}Zr. Moreover, it established $J^\pi=0^-$ for the g.s. of ^{98}Y with an expected shell model configuration of $(\nu s_{1/2} \pi p_{1/2})0^-$. Consequently, the $0^- \rightarrow 0^+$ transitions in $^{96,98}\text{Y} \rightarrow ^{96,98}$Zr similarly arise predominantly from the $\nu s_{1/2} \rightarrow \pi p_{1/2}$ decay. Furthermore, we postulate that the g.s. of ^{96}Sr, which is expected to be characterized by a strong $(\nu s_{1/2})^2 0^+$ component [18], β decays to the 0^- g.s. of ^{96}Y via a fast $\nu s_{1/2} \rightarrow \pi p_{1/2}$ first-forbidden transition. This transition is still to be verified as it is masked by an intense GT $0^+ \rightarrow 1^+$ β transition observed in this decay. These three transitions would form a region of fast $0^- \leftrightarrow 0^+$ β transitions in the vicinity of ^{96}Zr.

The fast first-forbidden $0^- \rightarrow 0^+$ β transitions near ^{96}Zr are related to the strong subshell closures at Z=40 and N=56 [1]. However, the $\nu s_{1/2}$ subshell closure at N=58 expected [7,19] from the similarity of ^{96}Zr and ^{98}Zr level schemes is not as strong as the $\nu d_{5/2}$ subshell closure at N=56 in ^{96}Zr. This is evident from much lower 0_2^+ energy in ^{98}Zr and disruption of normal filling of the shell model orbits at N=59. At N=58 the $\nu s_{1/2}$ orbit should be filled and the next neutron should go to the $\nu g_{7/2}$ orbit. However, $J^{\pi}=0^-$ for the g.s. of ^{98}Y (Z=39, N=59) indicates that the odd valence neutron occupies the $s_{1/2}$ orbit. A similar effect is observed [18] in ^{97}Sr (Z=38, N=59) where the odd N=59 neutron also resides in the spherical $s_{1/2}$ orbit.

Large mixing of the intruder deformed configurations with the g.s. wave functions can significantly alter the composition of the β-transition matrix element. However, studies of the intruder bands in ^{96,98}Zr imply [1,19,20] a rather weak deformation, $\beta_2 \sim 0.2$, for the 0_2^+ intruder states. The same conclusion can be drawn from the calculations of Heyde *et al.* [17] and the relatively large values of the mixing matrix elements for ^{96,98}Zr listed in Table 2. As a consequence, one does not expect strong admixtures of other configurations (like $\nu d_{3/2} \rightarrow \pi p_{3/2}$ [6]) to the main component $\nu s_{1/2} \rightarrow \pi p_{1/2}$ in the $0^- \rightarrow 0^+$ β decay of ^{96}Y and, perhaps to a lesser extent, of ^{98}Y, as indicated by its larger logft value.

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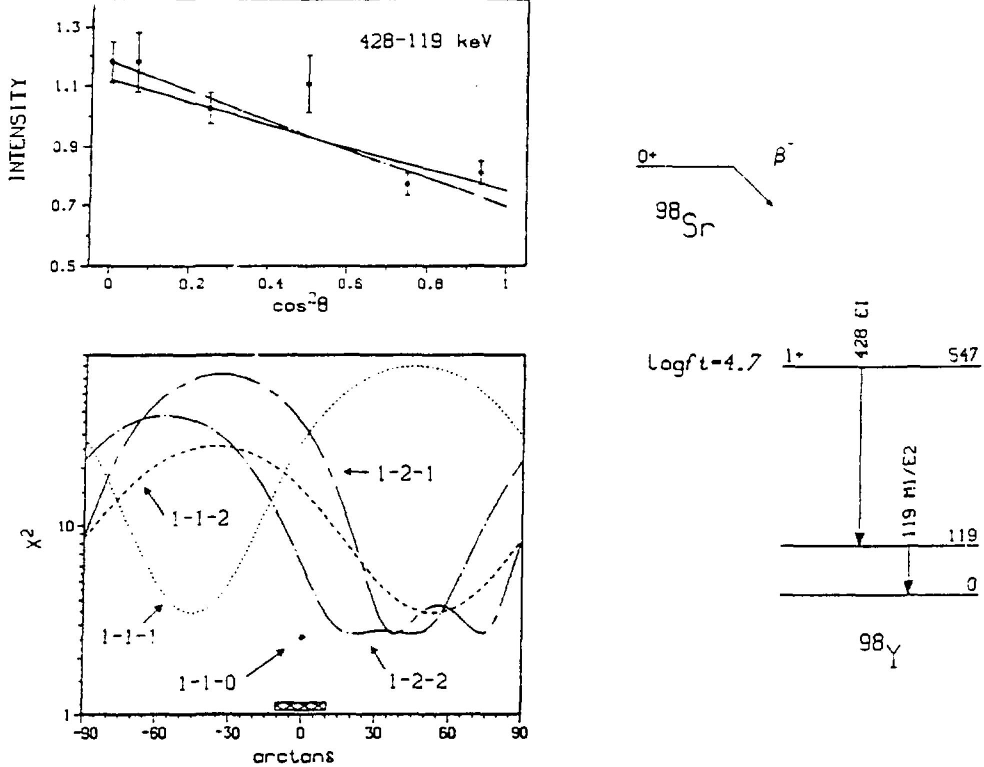

Fig. 1. Angular correlations for 428-119 keV cascade in ^{98}Y. The top panel indicates the best fit of the theoretical coefficients to the experimental data for 1-2-1, 1-2-2 (solid line) and 1-1-0, 1-1-1, and 1-1-2 (broken line) spin sequences. In the bottom panel χ^2 is plotted against δ(L+1/L) (expressed as *arctanδ*) for the same sequence of spins. The shaded area illustrates the acceptable δ mixing ratio for the 119-keV transition obtained from conversion coefficients. A partial decay scheme of ^{98}Sr [7] is illustrated on the right.

TABLE 1

E_γ [keV]	E_x [keV]	J	E_β [keV]	Q_β [keV]	$Q'_\beta - E_x - E_\beta$ [keV]
2941	4164		4820(45)	8984(45)	-
3228	4451		4483(88)	8934(88)	-
3310	4164		4854(62)	9018(62)	-
4450	4450		4430(62)	8881(62)	-
				Q'_β = 8963(41)	
213	1437	0^+	7437(76)	8874(76)	85(86)
268	1859	0^+	7049(46)	8908(46)	52(61)
1223	1223	2^+	7248(100)	8471(100)	488(108)
1591	1591	2^+	6605(80)	8196(80)	763(89)
1744	1744	2^+	4648(64)	6392(64)	2567(75)

TABLE 2

Nucleus	$E_{0_2^+}$ a) [keV]	B^2 b)	M [keV]	B^2 c)	M [keV]
$^{90}Zr_{50}$	1760.7	0.40(4)	863	0.26	772
$^{92}Zr_{52}$	1383.0	0.50(4)	692	0.33	650
$^{94}Zr_{54}$	1300.4	0.35(4)	620	0.23	547
$^{96}Zr_{56}$	1581.4	0.09(3)	453	0.04(2)	310
$^{98}Zr_{58}$	854.0	-	-	0.29	388
$^{100}Zr_{60}$	331.0	-	-	0.24	141

a) from Refs. 1,15; b) from Ref. 14.; c) from Refs. 1,7,15,16.