Search for closed-shell effects on the $E2/M1$ mixing of transitions in ^{116}Sn

G. Garcia-Bermudez,* S. L. Gupta,† N. C. Singhal, A. V. Ramayya, J. Lange,‡ and J. H. Hamilton
Physics Department, Vanderbilt University,§ Nashville, Tennessee 37235

N. R. Johnson
Oak Ridge National Laboratory,¶ Oak Ridge, Tennessee 37830

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Directional-correlation measurements of several cascades in ^{116}Sn have been made with a NaI-Ge(Li) detector system. Of particular interest is the 819-keV, $2^{+\prime} \rightarrow 2^+$ transition which was classified earlier as 90% $E2$ and almost pure $M1$ by two different groups. The γ-$\gamma(\theta)$ measurements of the $2^{+\prime}$(819-keV) $\rightarrow 2^+$ (1293-keV) $\rightarrow 0^+$ cascade yield A_2 and A_4 coefficients of 0.31(2) and 0.27(5), respectively. From these data a $\delta(E2/M1)$ of $-1.8(2)$ is obtained for the 819-keV transition, which corresponds to $76.4 \pm 3.7\%$ $E2$ radiation. The γ-ray intensities were measured more precisely.

[RADIOACTIVITY ^{116}In^m; measured γ-$\gamma(\theta)$, I_γ; deduced δ. NaI-Ge(Li) detectors.]

I. INTRODUCTION

The decay of ^{116}In^m (45 min) to the levels of ^{116}Sn has been investigated previously by Scharenberg, Stewart, and Wiedenbeck[1] and Bolotin.[2] They have measured the directional correlations of the γ transitions by employing two NaI detectors. Scharenberg, Stewart, and Wiedenbeck[1] reported a most probable value of $\delta(E2/M1)$ of -3.5 (quadrupole content 92%) for the 819-keV $2^{+\prime} \rightarrow 2^+$ transition. They did not give errors but only a range of $-1.7 \geq \delta \geq -40$, after correcting for 4^+-2^+-0^+ cascades with total intensity of approximately 50%. Bolotin,[2] however, reported a δ value of ≈ 0 (quadrupole content ≈ 0) in this case. Because of the apparent absence of any quadrupole strength in the $2^{+\prime} \rightarrow 2^+$ transition in his work, Bolotin[2] favored an interpretation that the $2^{+\prime}$ level at 2112 keV is composed primarily of admixtures of $(s_{1/2}, d_{3/2})$, $(d_{3/2})^2$, and $(h_{11/2})^2$ shell-model configurations.

Almost all $2^{+\prime} \rightarrow 2^+$ transitions in even-even nuclei have sizable $E2$ components[3] which indicate collective character of the levels. On the other hand, δ values approaching the single-particle limits have been suggested, though not definitely proven, for such transitions in a few closed-shell nuclei as discussed in a recent review.[3] The $2^{+\prime} \rightarrow 2^+$ transition in ^{116}Sn is the only case reported in a proton closed-shell nucleus where shell structure effects can be expected to be important. The previously proposed[4] decay scheme of ^{116}In^m modified to include our γ-ray intensities is shown in Fig. 1. The first 2^+ level at 1293 keV is known to be highly collective from inelastic scattering and reaction work.[5-8] The energy of the $2^{+\prime}$ level (2112 keV) is somewhat low for a two-phonon level and as well there is a third 2^+ state at 2230 keV seen in reaction work and the ^{116}Sb decay. Nevertheless, the $2^{+\prime}$ state still may be primarily collective in nature in which case the $2^{+\prime} \rightarrow 2^+$ transition is expected to be predominantly $E2$. Because of the discrepancy in the previous measurements[1,2] and the importance of the $E2$ transition strength in the $2^{+\prime} \rightarrow 2^+$ transition in determining the character of the 2112-keV level we have remeasured the directional correlations of the γ rays in ^{116}Sn with a NaI-Ge(Li) detector system. Our data show that the $2^{+\prime} \rightarrow 2^+$ transition is predominently $E2$.

II. EXPERIMENTAL TECHNIQUES

Sources of 54-min ^{116}In^m were produced by the ^{115}In$(n,\gamma)^{116}$In^m reaction in the Oak Ridge research reactor from a 99.5% enriched ^{115}In target. A fast rabbit system was employed for quick extraction of the radioactive sources. The sources

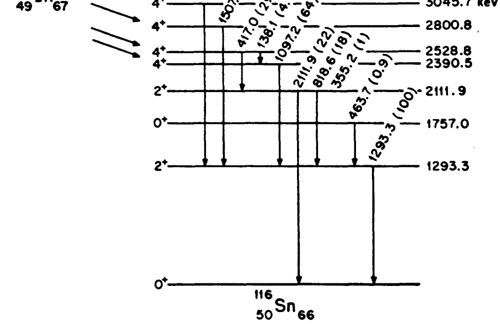

FIG. 1. Decay scheme of ^{116}In^m (Ref. 4). The relative γ-ray intensities shown on the decay scheme are from the present measurement.

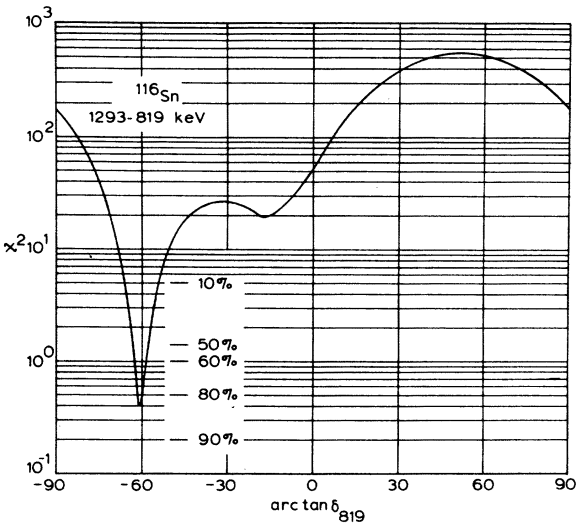

FIG. 2. Comparison of experimental and calculated values for the directional correlation of the 819-1293-keV cascade. The numbers given in percent are the confidence limits for two degrees of freedom.

were dissolved in weak HCl and these liquid sources were used for directional-correlation experiments.

The directional-correlation system employed a fixed Ge(Li) detector (resolution of 2.6 keV at 1332 keV and efficiency of 10%) and a 7.5-cm ×7.5-cm movable NaI detector. The source to detector distances were 7 cm. The NaI detector window was set on the photopeak of the $2^+ \to 0^+$, 1293-keV transition and the coincidence spectra from the Ge(Li) detector were stored in four subgroups of a Nuclear Data 4096-channel analyzer. The time resolution of the system was 30 nsec and the average true-to-chance ratio was ≈12/1. The source was centered to approximately 1% in counting rate with respect to the movable detector. Since the half-life of ^{116}In^m is 54 min, the data were collected for 6 min at each angle in a cycle. Each cycle consisted of accumulating data at 90, 120, 150, 180, 180, 210, 240, and 270°. The data from corresponding angles in the two quadrants were summed in the analyzer memory. Simultaneously, the total number of singles counts above 400 keV from both of the detectors was also measured for normalization purposes. A fresh source was prepared at the end of each cycle. The different sources used in the experiment varied within ~10% in intensity. A total of 12 cycles of data were recorded in the experiment.

The chance spectra were obtained by normalizing the 2112-keV peak in the singles to the 2112-keV peak seen in the coincidence spectra since the 2112-keV peak seen in each coincidence spectrum was attributed to pure random summing (see the decay scheme Fig. 1). The raw data were corrected for the chance coincidence events, normalized, and summed. From the resulting spectra, A_2 and A_4 coefficients were extracted with a least-

TABLE I. Results of γ-γ directional correlations in the decay of ^{116}In^m.

γ-$\gamma(\theta)$ (keV)	Unnormalized A_2	A_4	Normalized [a] A_2	A_4	$\delta = \frac{\langle L+1\rangle}{\langle L\rangle}$ [b]	Spin sequence
417-(819)-1293	0.02(2)	0.004(20)	−0.019(20)	0.017(24)	$0.8 \le \|\delta\| \le \infty$ [c]	4^+-($2^{+\prime}$-2^+)-0^+
464-1293	0.40(8)	1.22(15)	0.33(9) [d]	1.17(24) [d]		0^+-2^+-0^+
819-1293	0.36(2)	0.30(3)	0.31(2)	0.27(5)	−1.8(2)	$2^{+\prime}$-2^+-0^+
			0.23(2) [e]	0.0 [e]		
			0.12(6) [f]	0.14(7) [f]		
1097-1293	0.15(1)	0.011(13)	0.102 [a]	0.009 [a]		
			0.103(9) [e]	−0.009(22) [e]		4^+-2^+-0^+
			0.099(15) [g]	0.000(18) [g]		
1508-1293	0.17(2)	0.06(4)	0.11(2)	0.05(5)		4^+-2^+-0^+
			0.097(21) [e]	0.013(35) [e]		
			0.120(45) [f]	0.033(18) [f]		

[a] The experimental results were normalized to the theoretical values for the 1097-1293-keV cascade as described by Taylor (Ref. 11). The correction factors were applied to the other cascades.

[b] Sign convention of Krane and Steffen (Ref. 12) is used, and the values are from the normalized coefficients.

[c] The δ is for the $2^{+\prime} \to 2^+$ transition, where the limits are based on two limits on the A_2 and A_4 coefficients.

[d] The theoretical coefficients are0 .357 and 1.14.

[e] See Ref. 2. For the 819-1293-keV cascade, A_4 was set equal to zero.

[f] See Ref. 1. These values go to 0.14 and 0.28 when corrected for the presence of 4-2-0 cascades with total intensity of the order of 50%.

[g] See Ref. 1.

squares-fitting program. Solid angle correction factors for the two detectors were obtained from Refs. 9 and 10. The γ-ray singles spectra were measured with the Ge(Li) detector used in the γ-$\gamma(\theta)$ work.

III. RESULTS AND DISCUSSION

The results of the γ-$\gamma(\theta)$ measurements are given in Table I. Our A_2 coefficients (Table I) for the $4^+ \rightarrow 2^+ \rightarrow 0^+$ cascades that involve the 1097- and 1508-keV transitions yield δ values of 0.08 ± 0.02 ($M3 = 0.6\%$) and $0.12^{+0.05}_{-0.04}$ ($M3 = 1.4\%$), respectively. These $M3$ values are somewhat large in comparison to other $4^+ \rightarrow 2^+$ transitions and the A_2 coefficients are larger than those reported previously in Refs. 1 and 2. It is possible that the procedures of normalizing the data from the several sources may have introduced a small error that produced A_2 coefficients larger than for pure $E2$, $4^+ \rightarrow 2^+$ transitions. If present this could influence the other cascades. To test this possibility, we have used the procedure of Taylor[11] to normalize the 1097-1293 keV, $4^+ \rightarrow 2^+ \rightarrow 0^+$ cascade to the theoretical A_2 and A_4 coefficients for a pure $E2$ cascade. The correction factors were then applied to all the data and the new normalized coefficients for each cascade are given in columns 4 and 5. Note now that the $M3$ admixture in the 1508-keV transition vanishes within the experimental errors. On the other hand, the older work with the two NaI detectors could be slightly off and the small $M3$ admixtures real.

Our main interest in this work was to obtain the δ value of the 819-keV transition. The normalized values of A_2 and A_4 for the $2^{+\prime}$(819-keV) $\rightarrow 2^+$ (1293-keV) $\rightarrow 0^+$ cascade yield a δ value of -1.8 ± 0.2. The unnormalized data yield $\delta = -1.7 \pm 0.3$; however, we put greater confidence in the former value. In either case, the $E2$ admixture is large and essentially the same. Figure 2 shows the quality of the fitting and the statistical confidence level of the value of δ.

The mixing ratio (δ) of the 819-keV transition can also be obtained independently from the analysis of the 4^+ (417-keV) $\rightarrow [2^{+\prime}$(819-keV) $\rightarrow 2^+]$ (1293-keV) $\rightarrow 0^+$, 1-3 correlation. In this case the $4^+ \rightarrow 2^{+\prime}$ transition is assumed as pure quadrupole. The (1-3) directional-correlation coefficients are dependent on two factors: the mixing ratio δ of the $2^{+\prime} \rightarrow 2^+$, 819-keV transition and the $E0$ component[13] in that transition. The values of A_2 and A_4 obtained after correcting for an estimated 5% Compton coincidence background are given in Table I. For this cascade the normalizing procedure does make a sign change in A_2; however, the A_2 results agree within two standard deviations.

Under the assumption that the $E0$ component in this transition is negligible, which is reasonable based on a recent survey,[14] the $|\delta|$ obtained from the normalized values of A_2 and A_4 is between 1.4 and ∞ for 1σ and 0.8 to ∞ for 2σ to show δ is definitely not nearly zero. This result is consistent with the value obtained from the 1-2 directional correlation described above. Because of the large errors involved in this 1-3 cascade measurement, it is impossible to draw any conclusions about the magnitude of the $E0$ component.

The K-conversion coefficient of the $2^{+\prime} \rightarrow 2^+$, 819-keV transition has been measured by Cruetz, Grenacs, and Jones[15] and Pleiter.[4] Unfortunately the experimental values are consistent with the theoretical values[16] for either pure $M1$ or pure $E2$ transitions as shown in Table II.

The results for the $0^{+\prime}$ (464-keV) $\rightarrow 2^+$(1293-keV) $\rightarrow 0^+$ cascade are shown in Table I, and both the normalized and unnormalized coefficients are consistent with the expected theoretical values. All the above measurements have approximately the same statistical confidence based on a χ^2 test of 80% as obtained in the case of the 819-1293-keV cascade (see Fig. 2). The intensity of the 1752-keV transition is very weak and because of that the statistical accuracy obtained is very poor for the 1752-1293-keV cascade though the data are consistent with the spin sequence of $4^+ \rightarrow 2^+ \rightarrow 0^+$ within 2σ on A_2.

From our value of $\delta = -1.8 \pm 0.2$ for the 819-keV transition, the quadrupole content in the $2^{+\prime} \rightarrow 2^+$ transition is $76.4 \pm 3.7\%$. Our result is in near agreement with the $\delta = -3.5$ which Scharenberg, Stewart, and Wiedenbeck[1] give as their most probable value, but not with $\delta \approx 0$ as reported by Bolotin.[2] He assumed $A_4 = 0$ for this cascade in analyzing his data. The crucial point is that we do observe a sizable A_4 coefficient which can occur only if there is a sizable $E2$ admixture. Thus we conclude that the dominant decay is via $E2$ radiation. This result removes the one case where a δ near the single-particle Weisskopf limit had been reported in a proton closed-shell nucleus.

The γ-ray intensities were measured previously

TABLE II. Results of K-conversion coefficient measurements of the 819-keV transition (Refs. 4 and 15).

Transition energy	Spin sequence	Experimental α_K $\times 10^3$	Theoretical α_K $\times 10^3$	
			$M1$	$E2$
819	$2^{+\prime} \rightarrow 2^+$	2.0(2) (Ref. 4) 1.7(3) (Ref. 15)	2.17	1.75

TABLE III. γ-ray intensities in the decay of $^{116}In^{m}$.

Transition energy (keV) (Ref. 4)	Measured γ- ray intensities [a] (in %) (Ref. 17)	(Ref. 18)	Present work
138.1	3.8(9)	4.0(4)	4.7(2)
355.2	0.8(4)	0.85(8)	0.78(5)
417.0	32(5)	33(3)	29(2)
463.7	0.6(3)	0.89(9)	0.77(6)
818.6	15(2)	14(1)	12.3(7)
1097.2	56(5)	49(5)	59(3)
1293.3	84(4)	82(8)	84(4)
1507.5	12(2)	15(1)	9.9(5)
1752.4	2.0(5)	1.7(2)	2.3(2)
2111.9	16(2)	18(2)	15.7(9)

[a] The sum of the 2112- and 1293-keV γ intensities is equal to 100% since there is no ground-state β feeding.

by Da Costa *et al.*[17] and Fettweis and Verrier,[18] with relatively large errors (~10%). We have measured with improved accuracy the relative γ-ray intensities as given in Table III along with the earlier measurements.

The 1293-keV $E2$ transition from the first excited 2^+ state has been found[6] to proceed at about 10 times the single-particle rate. This 2^+ level has been interpreted as a collective one-phonon vibrational state. The ratio of the reduced transition probabilities $B(E2, 2^{+\prime} \to 0^+)/B(E2, 2^{+\prime} \to 2^+)$ is 0.01, which is consistent with a two-phonon interpretation for the 2112-keV level, although the energy is somewhat low. While the second $2^{+\prime}$ state decays to the first 2^+ state predominantly via the $E2$ mode, the 23.6% $M1$ admixture indicates sizable impurities if this is a two-phonon-type state. In addition the 2230-keV 2^+ level seen from the ^{116}Sb decay has a $B(E2, 2^{+\prime} \to 0^+)/B(E2, 2^{+\prime} \to 2^+) = 0.006$ in agreement with the phonon model. The near proximity of these 2^+ levels would suggest strong mixing; but, the absence of observable population of the 2112-keV level in the ^{116}Sb decay and the 2230-keV level in the $^{116}Sn^{m}$ decay argues against such mixing.

There is a strong transition from the 2112-keV level to the 1757-keV 0^+ state, $B(E2, 2^{+\prime} \to 0^+)/B(E2, 2^{+\prime} \to 2^+) = 5.5$. This ratio is orders of magnitude larger than recent limits[19] on such transitions between two-phonon states. This ratio and the very low energy (1757 keV) do not favor a two-phonon interpretation for the 0^+ state.

Beer *et al.*[20] have compared the experimental information on the levels in ^{116}Sn with several shell-model calculations which included various types of residual interactions. As they show, present calculations do not predict $2^{+\prime}$ states below 2300 keV.

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†On leave from the University of Delhi, India.

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‡Present address: University of Bochum, Bochum, W. Germany.

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