Gamma-gamma angular correlations of transitions in ^{94}Sr and ^{96}Sr

G. Jung* and B. Pfeiffer
II. Physikalisches Institut der J. Liebig Universität, 63 Giessen, Germany and Institut Max von Laue–Paul Langevin, 38042 Grenoble, France

L. J. Alquist and H. Wollnik
II. Physikalisches Institut der J. Liebig Universität, 63 Giessen, Germany

P. Hungerford and S. M. Scott
Physics Division, University of Sussex, Brighton, BN1 9QH, Sussex, England and Institut Max von Laue–Paul Langevin, 38042 Grenoble, France

W. D. Hamilton
Physics Division, University of Sussex, Brighton, BN1 9QH, Sussex, England
(Received 19 July 1979)

Angular-correlation measurements were made on ten direct cascades and four skip cascades in ^{94}Sr and on nine direct cascades in ^{96}Sr. These nuclei were populated by beta decay of isotopically pure ^{94}Rb and ^{96}Rb ion beams produced by fission and on-line mass separation. Correlations were measured for most of the intense transitions in coincidence with the $2^+ \rightarrow 0^+$ ground-state transition in both nuclei and two additional transitions in ^{94}Sr. Five levels in ^{94}Sr are given definite spin assignments and four levels tentative assignments. In ^{96}Sr definite spin assignments are made for four levels and tentative assignments for five levels. Values are listed for angular-correlation coefficients and, where applicable, multipole mixing ratios. Level systematics of neutron-rich even mass Sr isotopes are discussed within the context of assignments made here.

[RADIOACTIVITY ^{94}Rb, ^{96}Rb; measured γ-$\gamma(\theta)$ ^{94}Sr, ^{96}Sr deduced J, Π. Mass-separated ^{94}Rb, ^{96}Rb activity.]

I. INTRODUCTION

This work contains the results of angular-correlation measurements on transitions in ^{94}Sr and ^{96}Sr performed at the OSTIS mass separator facility.[1] This study was made in order to obtain details of the energy level position and spin-parity properties of neutron-rich transitional nuclei in the mass 100 region. Although interpretations of level systematics of neighboring neutron-rich even-even Zr and Mo isotopes have appeared in the literature,[2,3] sparse experimental data have prohibited such a comparison for the Sr isotopes in this deformed region. A recent study of ^{98}Rb decay[4] seems to indicate the onset of nuclear deformation at $N=60$ for the Sr isotopes. Therefore knowledge of the structure of the transitional ^{94}Sr and ^{96}Sr nuclei is particularly useful for systematic investigations of the microscopic structure of nuclear deformation in this region.

The initial experiments on the decay of ^{94}Rb and ^{96}Rb were beta-delayed neutron studies to determine half-lives[5-9] and delayed-neutron emission probabilities[5,6,9-11] of the Rb precursors. There is good agreement for the half-lives of ^{94}Rb(2.73 $\pm$0.01 s) (Ref. 5) and ^{96}Rb(0.205 $\pm$ 0.004 s) (Ref. 5) obtained by neutron counting techniques. A recent half-life measurement of ^{96}Rb(0.188 $\pm$ 0.002 s) (Ref. 12) by gamma multiscaling indicates a somewhat lower value. The average delayed-neutron emission probabilities for ^{94}Rb(9.49 $\pm$ 0.45%) (Refs. 6, 9–11, 13) and ^{96}Rb(12.6 $\pm$ 0.7%) (Refs. 6, 9, 14) from several references are in contrast with values (^{94}Rb : 13.7 $\pm$ 1.0% and ^{96}Rb : 17.0 $\pm$ 1.2%) reported in Ref. 5. The Q_{beta} values of ^{94}Rb(10300 $\pm$ 60 keV) (Ref. 15) and ^{96}Rb(11670 $\pm$ 130 keV) (Ref. 16) have recently been measured with an intrinsic Ge detector. Bonn *et al.*[17] have assigned 3 to the ground-state spin of ^{94}Rb on the basis of laser spectroscopic measurements, while the negative parity of this ground state is based on shell model considerations. Similar measurements on ^{96}Rb indicated[18] spins 1 and 2 for the ground state. This probably means that ^{96}Rb has an isomeric state which, in addition to the ground state, beta decays to levels in ^{96}Sr. This could explain the difference in half-life measurements for this isotope. An early gamma-ray spectroscopy measurement on ^{96}Rb decay was made by Gunther *et al.*[14] in which beta-gamma coincidences were made to reduce the gamma-singles background. Relatively few gamma rays of ^{96}Rb were identified in that study and, until very recently, no reports of the decay schemes of either ^{94}Rb or ^{96}Rb have appeared in the literature. The notable exceptions are the extensive Ge(Li)–Ge(Li) coincidence measurements for ^{94}Rb and ^{96}Rb decays reported by Jung *et al.*[19] Detailed level schemes for both decays were proposed on the basis of over 30 coincidence relationships per nucleus. Over 80% of the gamma-ray intensity appearing in the singles spectrum of the ^{94}Rb decay is placed in the ^{94}Sr scheme, and similarly, over 80% of the intensity in the singles spectrum of the ^{96}Rb decay is placed in the ^{96}Sr scheme. These decay schemes will be adopted for the present work, although not yet completed for the higher energy levels. For ^{94}Sr, since there is no ground-state feeding, estimates for β feeding and log*ft* values could also be made.

II. EQUIPMENT AND PROCEDURE

The angular-correlation apparatus in this experiment has been previously used to measure multipolarities of transitions between gamma and ground-state bands in ^{162}Dy and ^{164}Dy following thermal neutron capture.[20,21] It has also been used to investigate[22] cascades in ^{142}Ba and ^{144}Ba. The apparatus consists of two Ge(Li) detectors each positioned approximately 5 cm from the source. One detector is fixed and the other is automatically rotated in sequence to six angles between 90° and 180° with respect to the fixed detector. After 5 min of coincidence counting at one angle the movable detector rotates to an adjacent position until the six-position cycle is repeated. Timing signals from the detectors are processed by constant fraction discriminators which feed a time-to-amplitude converter (TAC). True plus random and random coincidences are established by corresponding gates on the TAC output. All coincidence events are stored in list mode format on magnetic tape via a computer-based multiparameter system (see Ref. 20).

An isotopically pure ion beam of Rb from OSTIS was deposited on an aluminized Mylar tape, which was moved away from the counting position at regular intervals in order to remove unwanted daughter decays. The source strength was monitored at each detector position by singles counting, which was later used to make a small correction (< 2%) to the coincidence counts due to source miscentering.

The data were first fit to the form

$$W(\theta) = 1 + a_2 U_2 P_2(\cos\theta) + a_4 U_4 P_4(\cos\theta),$$

where

$$a_k' = B_k(\gamma_1) A_k(\gamma_2)\,.$$

$B_k(\gamma_1)$, $A_k(\gamma_2)$ are the directional distribution coefficients which are given in terms of angular momentum coupling factors and the multipole mixing ratio δ. In the current work the sign convention of Krane and Steffen[26] is used for the mixing ratios. U_k are the de-orientation coefficients which are unity for the direct cascades. A finite solid angle correction for a point source is then made to the a_2, a_4 coefficients from the tables of Camp and van Lehn.[23] Finally the corrected angular-correlation coefficients are plotted along with elliptical curves of theoretical coefficients in which the mixing ratio is the variable parameter. Should a data point be consistent with only one cascade ellipse or single theoretical point, then a definite spin assignment can be made. Detailed discussions of the quantitative aspects of these analyses' procedures appear in Refs. 24 and 25.

III. RESULTS

Spin-parity assignments to levels in ^{94}Sr and ^{96}Sr are made under the assumption that no transition seen in the coincidence has multipole order greater than 2. In addition it is assumed that if the quadrupole ($L = 2$) mixing is greater than about 10% then the transition is $M1 + E2$ and connects states of even parity. This is justified by noting that electric quadrupole multipoles compete with the magnetic dipole multipoles ($M1 + E2$) much more successfully than is the case for $E1 + M2$ admixtures. Furthermore, levels that are assigned spin 2 and have significant gamma branching to the 0^+ ground state are assumed to have even parity.

A. Levels in ^{94}Sr

A partial level scheme for ^{94}Sr is given in Fig. 1 for those levels studied. Note that the level scheme is complete to the level at 2739 keV, and that all recorded transitions depopulating these levels are indicated. The first-excited-state-to-ground-state transition at 837 keV is the most intense in the ^{94}Rb decay and is one of the gating transitions for the angular-correlation coincidence spectra. This transition is assumed to be a pure $E2$, $2^+ \to 0^+$ transition. A gamma spectrum in coincidence with this transition can be seen in Fig. 2. Angular-correlation studies of transitions studied in coincidence with the 837 keV transition are shown in Fig. 1 as thick, solid arrows. Gamma-skip-gamma transitions are thick broken arrows. The percentage quadrupole admixture of the transitions is shown in Fig. 1 after the identifying values. Some representative directional correlation distributions are given in Fig. 3. Additional gates were set on the 1090 keV and 1309 keV transitions

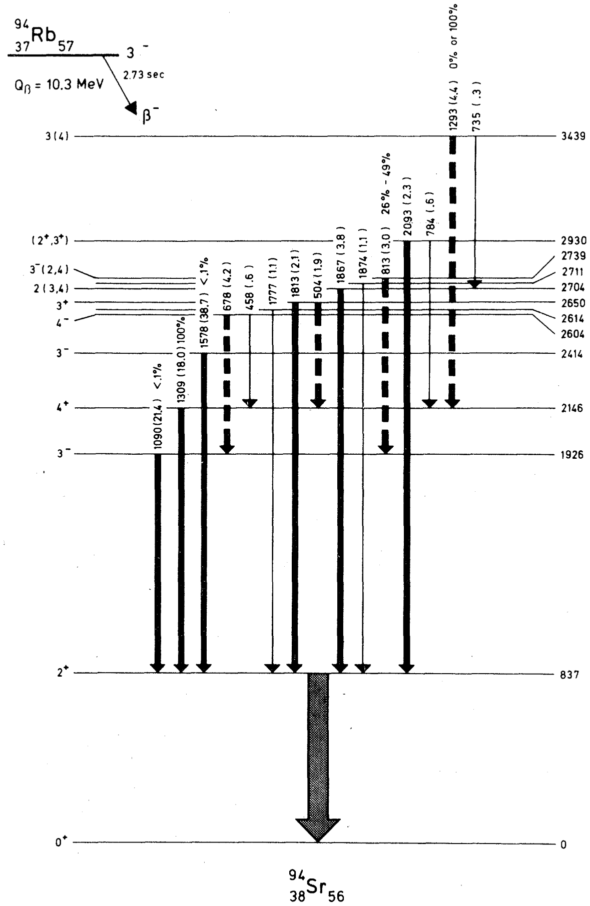

FIG. 1. Partial level scheme of ^{94}Sr. The scheme is complete to the 2739-keV level and all recorded transitions depopulating these levels are shown.

in order to remove some ambiguities in the spin assignments. These transitions were taken as pure electric dipole and pure electric quadrupole, respectively, as indicated by the 837-keV correlation data. The angular-correlation results obtained with the three gates are summarized in Table I. The results of individual levels will be discussed in order of increasing level energy.

1926-keV level. The experimental values for a_2 and a_4 of the 1090-837-keV cascade are plotted in Fig. 4. The data point lies very close to the 3-2-0 ellipse. The 1-2-0 ellipse is just outside the error bars and this spin sequence cannot be ruled out on this basis. However, if this level has a spin 1 the absence of a ground-state transition would be rather unusual. In addition, the 1926-keV level receives significant beta feeding (7.2%, $\log ft = 6.7$) which would be unlikely for a second forbidden beta decay (the parent ground state is presumed to be 3^-). A spin 1 assignment appears improbable here, and therefore spin 3 is assigned to this level. The amount of quadrupole mixing for the 1090-keV transition is less than 0.1%, which gives a negative parity assignment for the 1926-keV level.

2146-keV level. The experimental data points and angular-correlation fit function for the 1309–837-keV cascade are shown in Fig. 3. The experimental a_2, a_4 coordinate pair plotted in Fig. 4 has rather small errors and lies close to the 4-2-0 theoretical point, but is also consistent with the 2-2-0 and 3-2-0 ellipses. Further correlations were unable to limit the spin possibilities for this level. However, a spin 4^+ assignment is favored since this level is the only candidate below 2.6 MeV for the expected 4^+ state. This is supported by the absence of a ground-state transition.

2414-keV level. The experimental data points and angular-correlation fit function for the 1578–837-keV cascade are shown in Fig. 3. The values of the angular-correlation coefficients in Fig. 4 lie on the 3-2-0 ellipse, but since the error bars

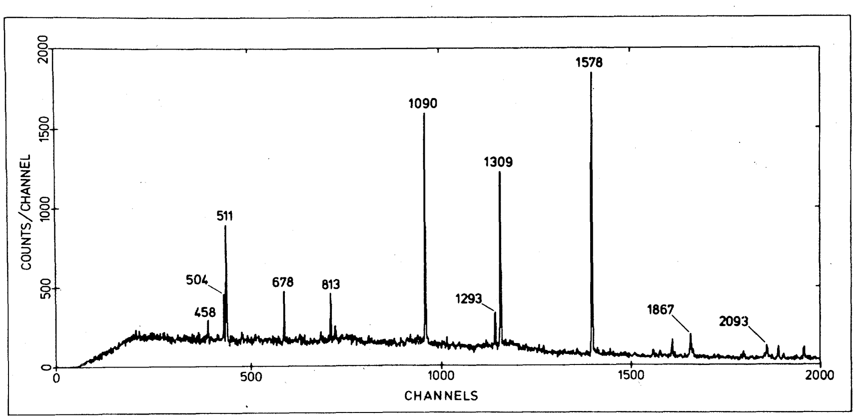

FIG. 2. A typical gamma spectrum obtained in coincidence with the 837-keV $2^+ \rightarrow 0^+$ transition in ^{94}Sr at the 180° position.

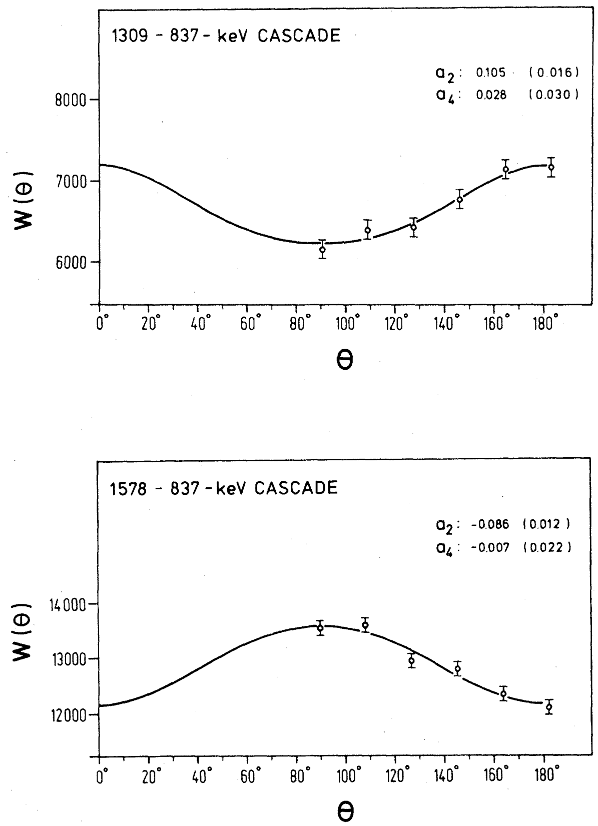

FIG. 3. Experimental data points and the angular-correlation function curves for selected cascades in ^{94}Sr.

intercept the 1-2-0 ellipse, spin 1 cannot be ruled out. There are, however, good reasons to eliminate spin 1. Other than the 1578-keV transition, which is the second most intense gamma in the level scheme, there is no other gamma ray de-exciting this level, and in particular there is no ground-state crossover which would be likely from a spin 1 level. The most compelling evidence is, however, the strong beta feeding (38%, $\log ft = 5.8$) to the 2414-keV level, indicating an allowed transition and a 3^- assignment. Also the 1578-keV transition is a pure electric dipole transition (<0.1% $L = 2$) which reaffirms a negative parity assignment to the 2414-keV level.

2604-keV level. The angular-correlation coefficients for the 678–(1090)–837-keV skip cascade are plotted in Fig. 5 with the assumption that the intermediate (1090-keV) transition is a pure electric dipole. This is consistent with the conclusions reached in the discussion of the 1926-keV level. It is clear from Fig. 5 that only spins 2 and 4 are consistent with the data point. The direct 678–1090-keV cascade gave the same result. In each case the 678-keV transition is significantly mixed, which indicates similar parity to the spin 3^- level at 1926 keV; thus implying negative parity. With a spin 2^- assignment to the 2604-keV level the 458-keV transition, which connects this level with the 4^+ level at 2146 keV, would have to be at least of multipole order $M2$, which is unlikely. Hence a spin 4^- assignment is made.

2650-keV level. For the 504–(1309)–837-keV skip cascade in Fig. 6 it is assumed that the 1309-keV skip transition is pure $E2$ (see discussion of the 2146-keV level). Only spin 2 can be excluded on the basis of this correlation. However, it should be noted that transitions from this level populate the 4^+ state at 2146 keV and the 2^+ state at 837 keV. If neither transition is octupole then the 2650-keV level must have spin 3 or 4. The direct 1813–837-keV cascade rules out the spin 4 possibility. In view of the large mixing (see Table I) for both transitions a 3^+ assignment is made for this level.

2704-keV level. Although the result for the 1867–837-keV cascade plotted in Fig. 4 does not intercept any curve, the 2-2-0 ellipse lies just outside the error bars. The 3-2-0 ellipse and 4-2-0 point are within 2 standard deviations of the data point but seem less likely prospects. No additional transitions populating or de-exciting this state indicate any preference so spin 2 is tentatively assigned.

2739-keV level. The location of the 813–(1090)–837-keV data point in Fig. 5 favors a spin 3 assignment for this level with significant (26–49%) electric quadrupole mixing and hence negative parity. However, the error in the a_4 coefficient prevents the exclusion of spin 2 or 4. The direct 813–1090-keV cascade could not further limit the possible spin assignments.

2930-keV level. The error in the a_4 value for the 2093–837-keV cascade includes all three spin ellipses in Fig. 4. However, the 4-2-0 theoretical point lies more than 2 standard deviations from the data point and spin 4 is thus excluded. The data point is located between the 2-2-0 and 3-2-0 ellipses, which favors spins 2 and 3 for the 2930-keV level assignment. For spin 2 a negative parity would imply a multipole order greater than or equal to $M2$ for the 784-keV transition thus positive parity is indicated. For the case of spin 3 the large quadrupole admixture for the 2093-keV transition (17–70%) indicates a positive parity assignment as well.

3439-keV level. In the analysis of the 1293–(1309)–837-keV skip cascade it is assumed that the intermediate 1309-keV transition is pure quadrupole (see the 2146-keV level). The a_2, a_4 data point is consistent with either spin 3 or 5, with spin 4 lying within two standard deviations as can

TABLE I. Results of the ^{94}Sr experiment.

Level (keV)	Cascade	a_2U_2 [a]	a_4U_4 [a]	Spin sequence	Parity of level	Mixing ratio	$L=2(\%)$
1926	1090–837	-0.059 ± 0.012	0.003 ± 0.022	3-2-0	−	$0.02^{+0.01}_{-0.02}$	0.0 to 0.1
2146	1309–837	0.105 ± 0.016	0.028 ± 0.030	4-2-0	+		
2414	1578–837	-0.086 ± 0.012	-0.007 ± 0.022	3-2-0	−	$-0.02^{+0.02}_{-0.01}$	0.0 to 0.1
2604	678–(1090)–837	-0.475 ± 0.039	0.042 ± 0.069	4-3-2-0	−	−0.71 to 1.81	33.7 to 76.6
	678–1090	0.273 ± 0.048	-0.034 ± 0.086	4-3-2	−	$-0.54^{+0.15}_{-0.31}$	$22.9^{+19.1}_{-9.9}$
						$-2.47^{+0.98}_{-1.37}$	$85.9^{+7.8}_{-17.0}$
2650	504–(1309)–837	0.142 ± 0.052	-0.086 ± 0.092	3-4-2-0	+	$-0.35^{+0.9}_{-0.7}$	$11.1^{+4.9}_{-3.8}$
						$-6.53^{+2.14}_{-5.14}$	$97.7^{+1.6}_{-2.6}$
	504–1309	0.252 ± 0.091	-0.067 ± 0.167	3-4-2	+	$-0.55^{+0.17}_{-0.30}$	$23.2^{+19.0}_{-10.5}$
						$-3.08^{+2.03}_{-2.53}$	$90.5^{+6.4}_{-15.1}$
	1813–837	0.250 ± 0.076	-0.005 ± 0.136	3-2-0	+	0.38 to 1.69	12.8 to 74.1
2704	1867–837	0.026 ± 0.044	0.147 ± 0.081	2-2-0		$0.29^{+0.07}_{-0.06}$	$7.9^{+3.3}_{-2.7}$
				3-2-0		0.13 ± 0.06	$1.7^{+1.9}_{-1.2}$
				4-2-0			
2739	813–(1090)–837	-0.109 ± 0.050	0.095 ± 0.091	3-3-2-0	−	$0.75^{+0.22}_{-0.16}$	$35.9^{+12.6}_{-9.9}$
				2-3-2-0		$-0.07^{+0.06}_{-0.05}$	$0.4^{+1.0}_{-0.4}$
				4-3-2-0		$-0.05^{+0.03}_{-0.07}$	$0.3^{+1.2}_{-0.3}$
2930	2093–837	0.250 ± 0.055	-0.014 ± 0.117	2-2-0		0.0 ± 0.17	<2.9
				3-2-0	+	0.45 to 1.53	17.0 to 70.0
3439	1293–(1309)–837	-0.087 ± 0.047	-0.078 ± 0.084	3-4-2-0		-0.06 ± 0.06	$0.4^{+1.0}_{-0.4}$
						$7.90^{+6.15}_{-2.43}$	$98.4^{+1.1}_{-1.6}$
	1293–1309	-0.209 ± 0.030	0.091 ± 0.055	4-4-2-0		(see text)	

[a] For direct cascades $U_2 = U_4 = 1$.

be seen in Fig. 5. Spin 3 is the more likely candidate here since the 3439-keV level receives significant beta feeding (4.7%, logft = 6.5). With a spin 5 assignment the beta decay would be at least first forbidden unique. For the 1293–1309-keV direct cascade none of the spin ellipses were within the error bars of the data point, but spins 4, 3, 5 are within two standard deviations. For spin 3 the 1293-keV transition is either pure dipole (<1.4%) or pure quadrupole (>96%).

In summary, spins and parities have been assigned to the first six excited states of ^{94}Sr. For the other levels tentative spin assignments were made with alternative choices given.

B. Levels in ^{96}Sr

A partial level scheme for ^{96}Sr is given in Fig. 7. The spin-parity assignments of the levels studied are made in accordance with the general guidelines discussed at the beginning of this section. The thick, solid arrows represent transitions studied with respect to the 815-keV first-excited-state-to-ground-state gating transition, which is the most intense gamma in the ^{96}Rb decay and assumed to be an $E2$, $2^+ \rightarrow 0^+$ transition. In addition to energy and intensity values for these transitions the percent of quadrupole admixture is also given. Note that the level scheme in Fig. 7 is complete to the level at 1852 keV and that all observed transitions from the levels are shown. Some directional correlation results are presented in Fig. 8.

A summary of the results of the angular-correlation studies on transitions between levels of ^{96}Sr is given in Table II. A discussion of the results for individual levels, in order of increasing level energy, follows.

1220-keV level: The data points and angular-

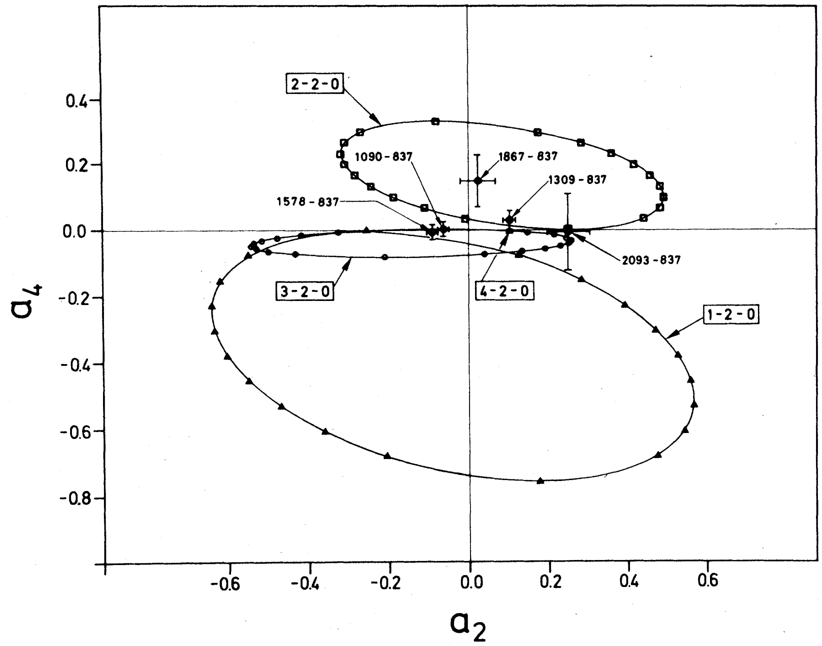

FIG. 4. The [94]Sr direct cascade results. The ellipse curves represent the locus of theoretical a_2, a_4 points parametrized in the dipole-quadrupole mixing ratio of the first transition. Each ellipse represents a spin sequence of a cascade with increments of 10% in the mixing ratio indicated by points on the curve. The experimental data points are identified by the energies of the transitions.

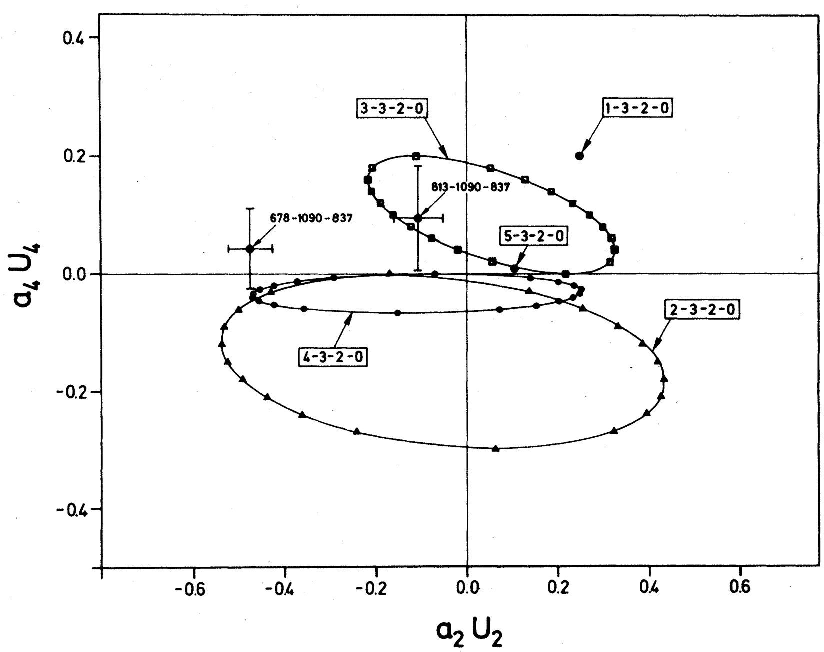

FIG. 5. Results of X-3-2-0 skip cascades for [94]Sr. The intermediate 1090-keV transition is assumed to be pure dipole (see discussion of 1926-keV level).

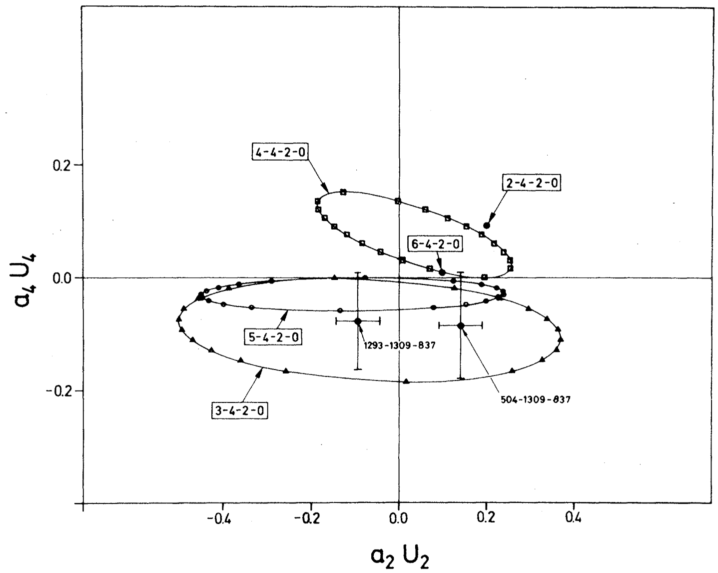

FIG. 6. Results of X-4-2-0 skip cascades for ^{94}Sr. The 1309-keV skip transition is assumed to be pure dipole (see discussion of the 2146-keV level).

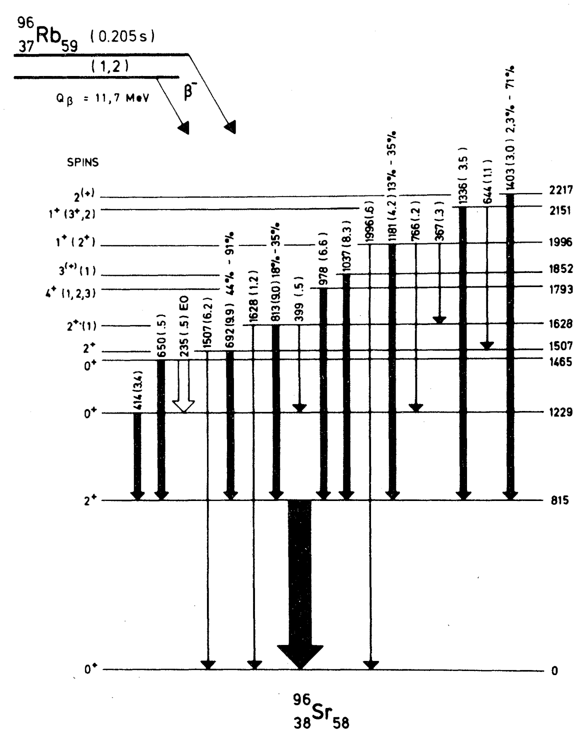

FIG. 7. Partial level scheme of ^{96}Sr. The scheme is complete to the 1852-keV level and all transitions depopulating these levels are shown.

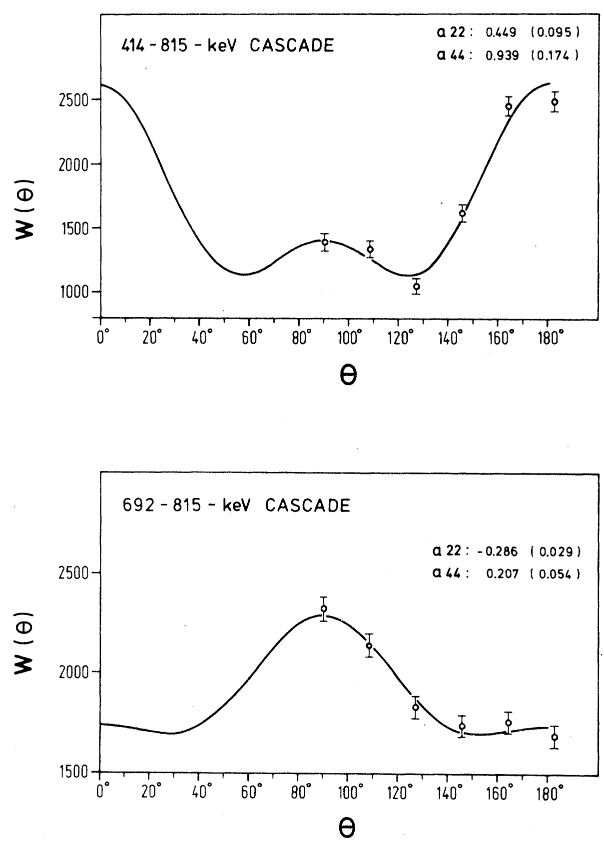

FIG. 8. Experimental data points and the angular-correlation function curves for selected cascades in ^{96}Sr.

TABLE II. Results of the ^{96}Sr experiment.

Level (keV)	Cascade	a_2U_2 [a]	a_4U_4 [a]	Spin sequence	Parity of level	Mixing ratio	$L=2(\%)$
1229	414–815	0.449 ± 0.095	0.939 ± 0.174	0-2-0	+		
1465	650–815	0.327 ± 0.180	1.135 ± 0.363	0-2-0	+		
1507	692–815	-0.286 ± 0.029	0.207 ± 0.054	2-2-0	+	0.89 to 3.16	44.1 to 90.9
1628	813–815	-0.152 ± 0.066	0.146 ± 0.105	2-2-0	+	$0.58^{+0.17}_{-0.12}$	$25.4^{+10.4}_{-7.8}$
				1-2-0		$-0.09^{+0.06}_{-0.05}$	$0.7^{+1.3}_{-0.6}$
1793	978–815	0.151 ± 0.051	0.040 ± 0.094	4-2-0	+		
				1-2-0		-0.36 ± 0.05	$11.2^{+3.0}_{-2.6}$
				2-2-0		$0.13^{+0.07}_{-0.06}$	$1.7^{+2.0}_{-1.3}$
				3-2-0		$0.33^{+0.13}_{-0.09}$	$10.1^{+7.1}_{-4.6}$
						$1.87^{+0.46}_{-0.40}$	$77.8^{+6.6}_{-9.3}$
1852	1037–815	-0.028 ± 0.040	-0.075 ± 0.073	3-2-0	(+)	$4.38^{+1.34}_{-0.87}$	$95.0^{+2.0}_{-2.5}$
						0.06 ± 0.05	$0.3^{+0.9}_{-0.3}$
				1-2-0		$-0.19^{+0.03}_{-0.04}$	$3.6^{+1.3}_{-1.2}$
1996	1181–815	0.304 ± 0.128	-0.188 ± 0.237	1-2-0	+	$-0.53^{+0.15}_{-0.20}$	$21.8^{+13.1}_{-9.1}$
2151	1336–815	0.210 ± 0.054	-0.156 ± 0.126	1-2-0	+	0.42 ± 0.06	15.3 ± 3.5
				3-2-0	+	-0.35 to -1.8	10.9 to 76.5
				2-2-0		0.05 ± 0.07	$0.3^{+1.2}_{-0.3}$
2217	1403–815	0.464 ± 0.112	0.181 ± 0.202	2-2-0	(+)	-0.15 to 1.56	2.3 to 70.8

[a] For direct cascades $U_2 = U_4 = 1$.

correlation fit function for the 414–815-keV cascade are shown in Fig. 8. The very large anisotropy seen here is a unique characteristic of a 0-2-0 spin cascade. Furthermore, the values of a_2 and a_4 are only consistent with a 0^+ spin assignment for the 1229-keV level.

1465-keV level. Although the 650-keV transition is in rather weak coincidence with the 815-keV gating transition the angular correlation is quite strong. And indeed the anisotropy is large enough to clearly indicate a 0-2-0 spin cascade. This assignment is supported by a recent internal conversion measurement[27] which indicated the total conversion of a 235-keV transition. This transition was identified as coming from the ^{96}Rb decay on the basis of half-life. Since this conversion line was also seen in the ^{97}Rb decay from beta-delayed neutron emission it could only come from a daughter of ^{96}Rb and cannot be attributed to a transition between isomeric states of the ^{96}Rb parent. The 235-keV $E0$ transition represents the energy level difference between the 1465- and 1229-keV levels. This transition is indicated by a thick open arrow in Fig. 7.

1507-keV level. The data points and angular-correlation fit curve are plotted in Fig. 8 for the 692–815-keV cascade. The a_2, a_4 coordinate pair in Fig. 9 clearly indicates a spin 2 assignment for this level. The location of the data point of the 2-2-0 ellipse implies significant (44–91%) electric quadrupole admixture, and thus even parity is assigned. This is further supported by a ground-state transition, which is presumably an electric quadrupole.

1628-keV level. Although the angular-correlation coefficients for the 813–815-keV cascade lie very near the 2-2-0 spin ellipse in Fig. 9, spin 3 or 1 cannot be excluded on this basis. There is, however, a ground-state transition from this level with sufficient intensity to rule out spin 3. Thus the assignment seems to favor spin 2 with a significant quadrupole admixture (18–35%) indicating positive parity.

1793-keV level. From the a_2, a_4 data point plotted in Fig. 9 the 978–815-keV cascade is consistent with spin 2, 3, or 4, with spin 1 less likely. A 4^+ assignment is preferred since this level is the *only* candidate for the expected 4^+ level, below 2.2 MeV.

1852-keV level. Spin 1 or 3 is indicated for this level from the plot of the correlation coefficients of the 1037–815-keV cascade in Fig. 9. There

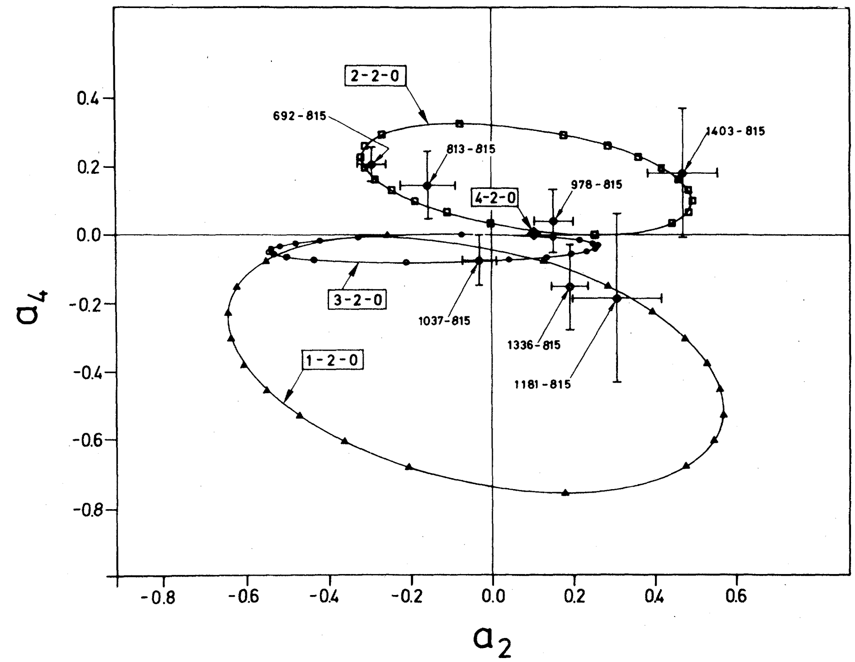

FIG. 9. Results of direct cascades for ^{96}Sr.

are, however, no observed transitions from this level to the 0^+ ground state or to either of the two low-lying 0^+ states. This tends to favor a spin 3 assignment for this level. In that case the 1037-keV transition would either be nearly a pure dipole (<1.2%) or a pure quadrupole (>92%). Pure quadrupole seems to be the more attractive candidate here since the data point itself lies on the 3-2-0 ellipse in the region of large admixture which then favors positive parity for this level.

1996-keV level. The angular-correlation coefficients for the 1181–815-keV cascade in Fig. 9 lie close to the 1-2-0 ellipse. However, owing to poor statistics, spins 3 and 2 cannot be excluded on this basis. A weak ground-state crossover and a transition to the spin 0^+ state at 1229 keV rules out spin 3 for the 1996-keV level. A 2^- assignment can be excluded due to the ground-state transition and the 766-keV transition to a 0^+ state. A 2^+ assignment is unlikely since the 1181-keV transition would connect 2^+ states with a low $E2$ admixture which has been observed infrequently. With a spin 1 assignment the 1181-keV transition would have significant electric quadrupole mixing (13–35 %) and thus imply even parity for the 1996-keV level.

2151-keV level. The correlation coefficients for the 1336–815-keV cascade in Fig. 9 are close to the 1-2-0 ellipse. However, the error in the a_4 coefficient is sufficiently large to include the 3-2-0 ellipse. In either case significant electric quadrupole mixing is indicated, which implies positive parity for this state. The data point is within two standard deviations of a region of the 2-2-0 ellipse corresponding to low quadrupole admixtures. A spin-parity 1^+ assignment is made here, with 3^+ and 2 not being completely ruled out.

2217-keV level. While the counting statistics are relatively poor for the 1403–815-keV cascade, the angular correlation is strong enough to indicate a spin 2 assignment for this level. The a_2, a_4 data point plotted in Fig. 9 lies on the 2-2-0 ellipse in an area indicating strong electric quadrupole mixing. However, large error bars, particularly in the a_4 direction, make smaller amounts of mixing possible. Thus the 2217-keV level is assigned spin 2 with tentative even parity.

In conclusion, the spins and parities are assigned for the first four excited states in ^{96}Sr on the basis of the angular correlations. The next five levels are given tentative assignments with at least one alternative spin choice.

IV. DISCUSSION

This study indicates that ^{94}Rb beta decays, by and large, to levels with spins 3 and 4 in ^{94}Sr. This is not so surprising in light of the spin 3^- assignment of the ^{94}Rb parent. The beta feeding to the spin 3 state at 2414 keV is, by far, the most intense (38%) to any of the excited states in ^{94}Sr. The strong beta feeding to this particular spin 3^- level is due to an allowed transition, which is consistent with the negative parity assignment of the parent nucleus. It has been noted in the introduction that ^{96}Rb beta decays from either a spin 1 or a spin 2 level. This appears to be consistent with the angular-correlation results since states of ^{96}Sr with a spin range of 0 to 3 are populated by beta decay, with the exception of the 4^+ level at 1793 keV. Positive parity is assigned to most of the levels studied in ^{96}Sr.

In light of the contribution of the present work detailed experimental information is now available for the Sr isotopes up to mass 98. Level systematics from ^{88}Sr to ^{100}Sr are shown in Fig. 10 and respective references given there. The reader is cautioned that while spins are given for several levels in ^{92}Sr from Ref. 28, the assignments up to now were made on the basis of gamma-ray intensities. However, preliminary results of a gamma-gamma directional correlation measurement in ^{92}Sr seem to confirm the 2^+ assignment to the second and third excited states. In addition, two 0^+ levels were found at 2088 and 2527 keV. Full details of these results will be given in Ref. 39.

The first 2^+ state falls from 1840 keV in the magic ^{88}Sr($N=50$) nucleus to a little over 800 keV and remains constant to $N=58$. Wollnik *et al.*[4] were the first to report the sharp fall of this level at $N=60$ and have suggested that this is indicative, as in the cases of Zr and Mo isotopes, of the onset of deformation of the Sr isotopes. The first 2^+ state is slightly lower in ^{100}Sr (Ref. 37) and still indicates deformation.

The first 4^+ state is more difficult to follow. The energy ratio of the 4^+ to 2^+ states begins at 1.99 for ^{90}Sr and suggests a two-phonon interpretation for this state and the nearby state at 1892 keV. This is supported by a large $B(E2)$ ratio for $(2_2^+\to 2_1^+)/(2_2^+\to 0_1^+)$ of 63 and a relatively large $E2$ admixture (20%) compared to single particle estimates. However, a nearby 0^+ state, which would complete the two-phonon triplet and which would be expected to be observed experimentally, is not seen, thus casting doubt on this interpretation. The 4^+-2^+ level energy ratio seems to increase rather dramatically in ^{92}Sr and is at a value of 2.56 in ^{94}Sr. The level energy ratio has a value of 2.99 in ^{98}Sr and 3.37 in ^{100}Sr (Ref. 37), giving further credence to the onset of deformation here.

Angular-correlation measurements in Ref. 24 and in this study indicate that the transitions from the 2_2^+ levels to the 2_1^+ first excited states in both ^{90}Sr and ^{96}Sr exhibit large $E2$ admixtures. This is also true for the $2_3^+\to 2_1^+$ transitions in ^{90}Sr and ^{96}Sr. This suggests that the 2_2^+ and 2_3^+ states may be interpreted as partly collective. The second and third 2^+ states do not, however, follow a regular systematic trend in energy with increasing neutron number. Starting from ^{90}Sr both states decrease dramatically and then increase substantially in energy at the $N=56$ subshell closure (the lowest available energy level for a possible

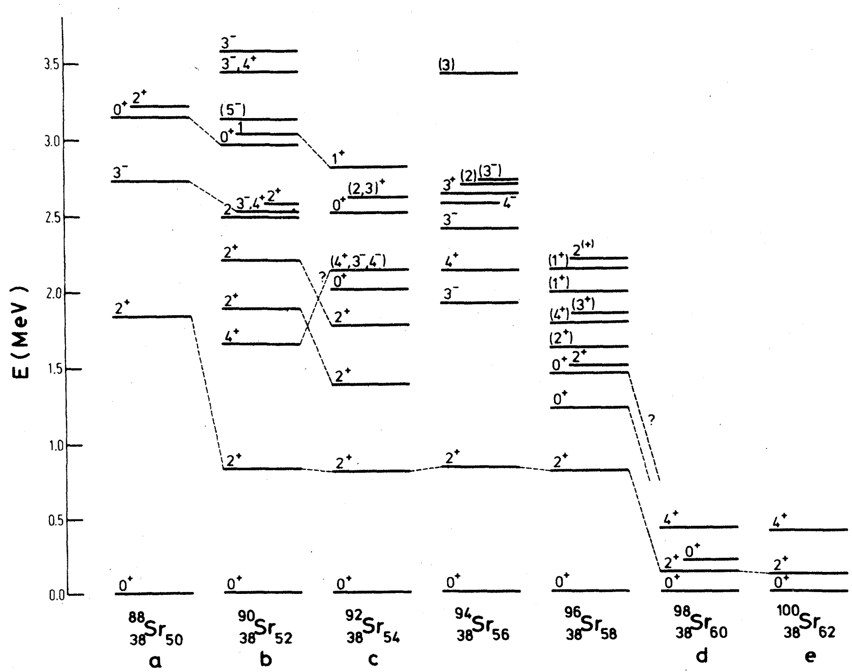

FIG. 10. Level systematics for the Sr isotpoes. a: Refs. 33–35; b: Refs. 24, 29, 36; c: Refs. 28, 39; d: Refs. 4, 38; e: Ref. 37.

spin 2 assignment in ^{94}Sr is already at 2604 keV). It would be interesting to know the multipole admixtures of the transitions from the second and third 2^+ levels to the 2^+ first excited state in ^{92}Sr.

The first 3^- state is definitely established in ^{88}Sr and ^{94}Sr and tentative assignments given in the intervening isotopes. This state seems to descend slowly from ^{88}Sr to ^{94}Sr. It should be noted here that there is disagreement for the 2207-keV level spin assignment in ^{90}Sr. While angular-correlation measurements[24] clearly assign 2^+ to this level, a (t, p) reaction study[29] indicates a $3^-(4^+)$ assignment.

States with 0^+ have been measured at about 3 MeV in ^{88}Sr, ^{90}Sr, and at 2 and 2.5 MeV in ^{92}Sr. However, no 0^+ state was observed in the angular correlations in ^{94}Sr. Recent internal conversion measurements[27] at this mass also did not provide any indication of an excited 0^+ spin state; however, this is not unexpected since a 0^+ state would not be fed by β decay from the 3^- ground state of the parent. Although the first 0^+ states in ^{88}Sr and ^{90}Sr appear at roughly the same energies (3155 and 2971 keV) there is a lowering of the 0^+ level to 1229 keV at $N = 58$ in ^{96}Sr. It has been suggested that this effect, which is seen in the systematics of even-even Zr and Mo isotopes, may be due to the existence of shape isomerism,[2,30] and arises from co-existing rotational and beta/gamma-vibrational bands. In this picture a highly deformed secondary shape minimum is associated with the excited 0^+ state, possibly due to the deformed proton shell structure ($Z = 38$ for the Sr isotopes). As the number of neutrons increases the neutron shell structure acts to create greater stability for the secondary deformed shape, and hence a lowering of 0^+ levels until the deformed state becomes the ground state at $N = 60$ as proposed for Zr and Mo. While this interpretation could also be applied to the Sr isotopes, it should be pointed out that there are no substantial experimental data which directly support this view.

Federman *et al.*[3,31,32] have attempted to explain the deformed shape transition of neutron-rich Zr and Mo isotopes in terms of the isoscalar ($^3S_1$) neutron-proton interaction in the framework of the shell model. These authors point out that the $^3S_1$ attraction between neutrons and protons in orbitals with good spatial overlap is a common ingredient in deformation of light and heavy nuclei. A case in point in the light region is the strong interaction between the $1d_{5/2}$ and $1d_{3/2}$ orbitals in ^{18}F. Under this interpretation deformation in the Sr isotopes would be due to a strong attraction between protons and neutrons promoted into the $1g_{9/2}$ and $1g_{7/2}$ orbitals through a polarization effect.[31] The sudden appearance of low-lying 0^+ excited states in ^{96}Sr may be viewed in analogy to the explanation of Federman *et al.*[3] for the lowering of the 0^+ excited state in the Zr isotopes; that is, as the $g_{7/2}$ orbital achieves greater neutron population in going from ^{94}Sr to ^{96}Sr, the protons corresponding to the 0^+ ground state remain in orbitals (probably $p_{1/2}$, $f_{5/2}$) which do not have strong n-p interactions. On the other hand, the excited 0^+ states, which may have significant admixtures of $1g_{9/2}$ proton orbitals, strongly feel the n-p interaction between the $1g_{7/2}$-$1g_{9/2}$ "partner" orbits as two neutrons are added. The effect is the lowering of the excited 0^+ states. It would be particularly interesting to make energy level calculations for the Sr isotopes, using the framework of this interpretation.

Future experimental work on the Sr isotopes could complement the level systematics presented in this work. With improved ion beam intensity at OSTIS, through the development of a new ion source, it is hoped that more detailed spectroscopic measurements can be made on ^{98}Rb and ^{100}Rb decays.

ACKNOWLEDGMENTS

The authors wish to acknowledge the support of the Institut Laue-Langevin and the Bundesminister für Forschung und Technologie. In addition, one of the authors (LJA) would like to gratefully acknowledge the Alexander von Humboldt-Stiftung for financial support.

*This work will be part of the doctoral thesis of G. Jung.

[1]K. D. Wünsch, Nucl. Instrum. Methods 155, 347 (1978).
[2]R. K. Sheline, I. Ragnarsson, and S. G. Nilsson, Phys. Lett. 41B, 115 (1972).
[3]P. Federman, S. Pittel, and F. Campos, Phys. Lett. 82B, 9 (1979).
[4]H. Wollnik, F. K. Wohn, K. D. Wünsch, and G. Jung, Nucl. Phys. A291, 355 (1977).
[5]P. L. Reeder, J. F. Wright, and L. J. Alquist, Phys. Rev. C 15, 2108 (1977).
[6]E. Roeckl, P. F. Dittner, R. Klapisch, C. Thibault, C. Rigaud, and R. Prieels, Nucl. Phys. A222, 621 (1974).
[7]G. Rudstam and E. Lund, Phys. Rev. C 13, 321 (1976).
[8]E. Lund and G. Rudstam, Phys. Rev. C 13, 1544 (1976).
[9]C. Ristori, J. Crançon, K. D. Wünsch, G. Jung,

R. Decker, and K. L. Kratz, Z. Phys. 290, 311 (1979).
[10]M. Asghar, J. Crançon, J. P. Gautheron, and C. Ristori, J. Inorg. Nucl. Chem. 37, 1563 (1975).
[11]M. Asghar, J. P. Gautheron, G. Bailleul, J. P. Bocquet, J. Greif, H. Schrader, G. Siegert, C. Ristori, J. Crançon, and G. I. Crawford, Nucl. Phys. A247, 359 (1975).
[12]P. Peuser, H. Otto, M. Weis, G. Nyman, E. Roeckl, J. Bonn, L. von Reisky, and C. Spath, Z. Phys. A289, 219 (1979).
[13]T. Izak-Biran and S. Amiel, Nucl. Sci. Eng. 57, 117 (1975).
[14]H. Gunther, G. Siegert, K. Wünsch, and H. Wollnik, Nucl. Phys. A242, 56 (1975).
[15]K. D. Wünsch, R. Decker, H. Wollnik, J. Muenzel, G. Siegert, G. Jung, and E. Koglin, Z. Phys. A288, 105 (1978).
[16]F. Münnich, Workshop on Nuclear Spectroscopy of Fission Products at Institut Laue-Langevin, Grenoble, France, 1979, Institute of Physics Conference Series, Bristol (to be published).
[17]J. Bonn, F. Buchinger, P. Dabkiewicz, H. Fisher, S. L. Kaufmann, H. J. Kluge, H. J. Kremmling, L. Kugler, R. Neugart, E. W. Otten, L. von Reisky, J. M. Rodriguez, H. J. Steinacher, and K. P. C. Spath, Hyp. Int. 4, 174 (1978).
[18]J. Bonn, private communication.
[19]G. Jung, E. Koglin, K. D. Wünsch, H. Wollnik, E. Monnand, and F. Schussler, Annex to the Annual Report (1978) of the Institut Laue-Langevin Grenoble, Experiment No. 03-03-062, p. 46.
[20]P. Hungerford, Ph.D. thesis, Sussex University, Sussex, England, 1979 (unpublished).
[21]P. Hungerford, W. D. Hamilton, S. M. Scott, and D. D. Warner, J. Phys. G (to be published).
[22]S. M. Scott, D. D. Warner, W. D. Hamilton, P. Hungerford, G. Jung, K. D. Wünsch, and B Pfeiffer, J. Phys. G 5, L187 (1979).
[23]D. C. Camp and A. L. van Lehn, Nucl. Instrum. Methods 76, 192 (1969).
[24]L. J. Alquist, Ph.D. thesis, Iowa State University, 1975 (unpublished).
[25]W. D. Hamilton in *Electromagnetic Interaction in Nuclear Spectroscopy*, edited by W. D. Hamilton (North-Holland, Amsterdam, 1975).
[26]K. S. Krane and R. M. Steffen, Phys. Rev. C 2, 724 (1970).
[27]F. Schussler, E. Monnand, J. A. Pinston, G. Jung, and B. Pfeiffer, Annex to the Annual Report (1979) of the Institut Laue-Langevin, Grenoble, Experiment No. 03-03-101.
[28]R. J. Olson, W. L. Talbert, Jr., and J. R. McConnell, Phys. Rev. C 5, 2095 (1972).
[29]E. R. Flynn, O. Hansen, J. D. Sherman, N. Stein, and J. W. Sunier, Nucl. Phys. A264, 253 (1976).
[30]T. A. Khan, W. D. Lauppe, K. Sistemich, H. Lawin, and H. A. Selic, Z. Phys. A284, 313 (1978).
[31]P. Federman and S. Pittel, Phys. Lett. 69B, 385 (1977).
[32]P. Federman and S. Pittel, Phys. Lett. 77B, 29 (1978).
[33]W. P. Alford, R. C. Anderson, P. A. Batay-Csorba, D. A. Lind, H. H. Wieman, and C. D. Zafiratos, Nucl. Phys. A293, 83 (1977).
[34]K. K. Sath, K. A. Buzard, J. Picard, and G. Bassini, Phys. Rev. C 10, 1928 (1974).
[35]M. J. Schneider, R. E. Anderson, and P. G. Brabeck, Nucl. Phys. A246, 156 (1975).
[36]H. Huang, B. P. Pathak, R. Iafigliola, L. Lessard, and J. K. P. Lee, Z. Phys. A282, 285 (1977).
[37]E. Koglin, private communication.
[38]F. Schussler, J. A. Pinston, E. Monnand, G. Jung, E. Koglin, B. Pfeiffer, R. Janssens, and J. van Klinken, Nucl. Phys. (to be published).
[39]L. J. Alquist, H. Wollnik, G. Jung, B. Pfeiffer, P. Hungerford, S. M. Scott, and W. D. Hamilton, Nucl. Phys. (to be published).