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Spectroscopy of ^{95}Ru at high spins

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High spin states in the $N=51$ nucleus ^{95}Ru were populated and studied using the reaction ^{64}Zn(^{35}Cl,3*pn*)^{95}Ru at a beam energy of 140 MeV. Gamma-ray intensities and gamma-gamma coincidences were measured. Multipolarities of the transitions were extracted assuming stretched transitions. Forty new transitions have been found. The positive and negative parity bands have been extended up to spins of $43/2^+$ and $39/2^-$, respectively. The level scheme can be well understood up to moderate spins in terms of spherical shell model calculations within a limited configuration space. A weak coupling scheme in which a $2d_{5/2}$ neutron is coupled to the excited ^{94}Ru core was found to work reasonably well and reproduced the main features of the observed ^{95}Ru yrast spectrum. A more rigorous approach to understanding the structure of these high spin states is the breaking of the $N=50$ neutron core. The top three transitions in the positive parity band (492, 599, and 744 keV) appear to be an indication of collective behavior.

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I. INTRODUCTION

Low lying levels in nuclei that lie near and at the neutron magic number $N=50$ are well described by taking ^{88}Sr as core and the valence nucleons occupying the $(2p_{1/2}, 1g_{9/2})$ configurations [1,2]. In our earlier study of the nucleus ^{93}Tc we attempted to describe the observed high spin states on the basis of the spherical shell model calculations with the valence protons occupying the enlarged $(1f_{5/2}, 2p_{3/2}, 2p_{1/2}, 1g_{9/2})$ configuration space with ^{78}Ni as the closed core [3]. Another possible mechanism to generate the higher angular momentum states is to break the $N=50$ closed shell [4]. Therefore, it appears interesting to systematically study the high spin states in the $N=50$ and neighboring nuclei in order to understand the possible mechanism for generating these states.

Another motivating factor for the present study was the interesting experimental results for Sn isotopes with $Z=50$ [5–7] and the recently reported [8] study of ^{117}Sb, which has $Z=51$. New deformed intruder states were found at high spin in these nuclei. This fascinating aspect, with a desire to systematically explore the possible mechanism for the high spin states, has motivated us to investigate nuclei at and near the neutron magic number $N=50$. In this paper we report our study of the nucleus ^{95}Ru.

II. EXPERIMENTAL DETAILS AND ANALYSIS

High spin states in ^{95}Ru were populated using the ^{64}Zn(^{35}Cl,3*pn*)^{95}Ru reaction at a beam energy of 140 MeV. The ^{35}Cl beam was provided by the 15 UD Pelletron Accelerator at the Nuclear Science Centre (NSC), New Delhi. The relative production cross sections of the residues in the above reaction were consistent with those predicted by the statistical model code CASCADE. The isotopically enriched (99%) ^{64}Zn target had a thickness of about 1.3 mg cm^{-2} and a 25-mg cm^{-2} Pb backing.

Gamma-gamma coincidences were measured using the gamma detector array (GDA) at the NSC. At the time of this experiment the GDA consisted of five Compton suppressed high purity germanium detectors and 14 element bismuth germanate (BGO) multiplicity filter. The details of the GDA can be found in Ref. [3], wherein we had reported the high spin spectroscopy of ^{93}Tc.

Previous studies of ^{95}Ru by Chowdhury *et al.* [9] and Goswami *et al.* [10] had used (charged particle, *xn*) reactions with relatively light projectiles like ^{7}Li ions and alpha particles. In the present work, a heavy ion beam of ^{35}Cl ions has been employed. This significantly changed the situation—the higher angular momentum states in ^{95}Ru were excited.

The ^{95}Ru gamma rays have been placed in the level scheme using the observed coincidence relationship and the intensity argument for the gamma rays. The typical gamma coincidence rate was about 150 counts per second and about 25×10^6 events corresponding to a twofold or higher fold coincidence (within a system timing resolution of 40 ns) were recorded in the list mode. The list mode data consisted of a pattern word identifying the detectors in coincidence, their energies, the multiplicity information, and the timing information between the two coincident gamma rays. The timing information was recorded using the time-to-digital convertors (TDC's)

[17]. The singles were gated with the $K>2$ condition, where K was the number of BGO elements that had fired in the multiplicity filter.

The pulse heights in all the detectors were software gain matched, and the data was sorted out into a 1024×1024 and E_γ-E_γ matrix. From the processed data background subtracted one-dimensional histograms for gamma energies in one detector gated by a suitable transition in the other detector could be generated. The amplifier gains in the experiment were kept low enough so that gamma rays up to 2.7 MeV energy could be recorded. Multipolarities of the observed gamma rays were assigned using the procedure described in Refs. [3,11].

III. EXPERIMENTAL RESULTS

In this experiment we have observed 40 new gamma rays belonging to the nucleus ^{95}Ru. Table I gives the excitation energy (E_x), transition energy (E_γ), the relative intensity (I_γ), and the spin assignment of the gamma rays. All the intensities were efficiency corrected.

Figures 1 and 2 show the spectra that were in coincidence with the 255 and 281 keV transitions, respectively. These transitions (gates) belong to the positive and negative parity bands, respectively, and the projected spectra have been shown in the entire energy range. The new gamma rays observed in the positive parity band were 672 keV ($E2$), 2141 keV ($M1$), 2275 keV ($M1$), 574 keV ($M1$), 705 keV ($M1$), 181 keV ($M1$), 886 keV ($E2$), 492 keV ($M1$), 599 keV ($M1$), and 744 keV ($M1$). These transitions have been placed above the $25/2^+$ level in the positive parity band. The multipolarity assignment was based on the procedure referred to in the previous section. The 255 keV transition is in coincidence with itself (Fig. 1). This confirms the earlier finding [9,10] that there were two 255 keV gamma rays. The new gamma rays observed in the negative parity band were 224 keV ($M1$), 239 keV ($M1$), 872 keV ($M1$), 158 keV ($M1$), 329 keV ($M1$), 703 keV ($M1$), 1289 keV ($E2$), 1073 keV ($M1$), 1753 keV ($M1$), 235 keV ($M1$), 2534 keV ($E2$), 1907 keV ($E2$), 1054 keV ($E2$), 928 keV ($E2$), 985 keV ($E2$), 508 keV ($E2$), 552 keV ($E2$), 1111 keV ($E2$), and 1030 keV ($E2$). We have gated on all the gamma rays and looked at the intensity flow above and below the gated gamma ray and feel reasonably certain about the position of these new gamma rays in the level scheme.

Some of these new gamma rays were found to be in-band cross transitions in both the positive and negative parity bands. These were found to be $E2$ in character, with energies of 886, 928, 985, 552, 508, 1111, and 1030

TABLE I. Excitation energies (E_x), transition energy (E_γ), relative intensity (I_γ), and spin states in ^{95}Ru.

E_x (keV)	E_γ (keV)	I_γ	$J_i^\pi \rightarrow J_f^\pi$
1352.1	1352.1	100.0(3)	$9/2^+\rightarrow5/2^+$
942.2	942.2	12.2(7)	$7/2^+\rightarrow5/2^+$
1352.1	410.2	3.8(9)	$9/2^+\rightarrow7/2^+$
2029.4	677.3	68.8(4)	$13/2^+\rightarrow9/2^+$
2284.1	254.7	94.4(3)^d	$17/2^+\rightarrow13/2^+$
2538.8	254.7		$21/2^+\rightarrow17/2^+$
3831.1	1292.3	46.6(5)	$25/2^+\rightarrow21/2^+$
4503.7	672.6	31.6(3)	$29/2^+\rightarrow25/2^+$
6644.6	2140.9	6.9(1.8)	$31/2^+\rightarrow29/2^+$
6778.4	2274.7	5.5(4.0)	$(31/2^+)\rightarrow(29/2^+)$
7218.5	573.9	4.9(7)	$33/2^+\rightarrow31/2^+$
8104.5	885.9	2.8(1.1)	$37/2^+\rightarrow33/2^+$
7923.5	704.9	2.4(1.1)	$35/2^+\rightarrow33/2^+$
8104.5	181.0	2.1(1.1)	$37/2^+\rightarrow35/2^+$
8596.7	492.2	1.1(1.6)	$39/2^+\rightarrow37/2^+$
9195.5	598.8	a	$41/2^+\rightarrow37/2^+$
9939.7	744.2	w	$43/2^+\rightarrow41/2^+$
2493.4	1140.8	10.4(1.9)	$13/2^-\rightarrow9/2^+$
2246.9	894.8	12.5(5)	$11/2^{(-)}\rightarrow9/2^+$
2493.4	246.4	10.4(4)	$13/2^-\rightarrow11/2^{(-)}$
3478.0	985.0	3.8(2.0)	$17/2^-\rightarrow13/2^-$
2774.7	281.3	16.6(2)	$15/2^-\rightarrow13/2^-$
3478.0	703.3	a	$17/2^-\rightarrow15/2^-$
3702.2	927.6	18.3(4)	$19/2^-\rightarrow15/2^-$
3702.2	224.2	4.8(6)	$19/2^-\rightarrow17/2^-$
3986.1	508.1	8.2(9)	$21/2^-\rightarrow17/2^-$
3986.1	283.4	18.9(2)	$21/2^-\rightarrow19/2^-$
4193.0	206.9	22.7(4)	$23/2^-\rightarrow21/2^-$
4744.9	551.9	2.5(2.0)	$27/2^-\rightarrow23/2^-$

keV. For example, in Fig. 3 we show the partial gated spectrum for the in-band 985 keV cross transition belonging to the negative parity band. A gate on the 985 keV ($17/2^- \rightarrow 13/2^-$) transition showed all the members of the negative parity band except the two gamma rays 281 keV ($15/2^- \rightarrow 13/2^-$) and 703 keV ($17/2^- \rightarrow 15/2^-$). Similarly a gate on either the 281 or 703 keV showed that the 985 keV gamma ray was not in coincidence with them, while all other members of the band were. This is shown in Fig. 3. The existence of these and the other cross transitions makes the proposed level scheme very likely; the depopulation pattern gets tied down. Figure 4 shows the proposed level scheme for ^{95}Ru. Newly observed transitions in the present work have been indicated with dots.

The positive parity band was extended up to a spin of $43/2^+$, and the negative parity band was extended up to a spin of $39/2^-$. The last few transitions in the negative parity band were too weak to enable us to draw definite conclusions about their multipolarities. These are marked by showing their spin parity assignment in a bracket.

We have also observed several gamma rays connecting the positive and negative parity bands. The 464, 746, 291, 715, 1655, 364, 1127, 623, 788, 825, 1141, and 1305 keV gamma rays corresponded to the interband cross transitions connecting the two main bands. These interband transitions may not be stretched. This is the reason why no definite conclusions could be drawn about their multipolarities. Tentative spin and parity assignments are shown in the bracket in Fig. 4.

In addition to the new transitions, which we have placed in the level scheme, we have observed 72, 74, 498, and 1318 keV transitions, which are in coincidence with some transitions placed in the level scheme. We have not been able to place these gamma rays in the decay scheme. Also the 491, 329, and 746 keV transitions are shown in Fig. 4 by dotted lines, since we were not reasonably sure of their placement in the level diagram.

We have found several discrepancies in the earlier work [9,10]. In an earlier work by Goswami *et al.* [10] it was reported that transitions 207, 313, and 363 keV are

TABLE I. (*Continued*).

E_x (keV)	E_γ (keV)	I_γ	$J_i^\pi \rightarrow J_f^\pi$
4505.9	312.9	30.4(4)	$25/2^- \rightarrow 23/2^-$
4744.5	238.6	22.2(4)	$27/2^- \rightarrow 25/2^-$
5774.6	1030.1	28.2(4)	$31/2^- \rightarrow 27/2^-$
5616.8	1110.9	4.4(9)	$29/2^- \rightarrow 25/2^-$
5616.8	871.9	9.6(9)	$29/2^- \rightarrow 27/2^-$
5774.6	157.7	3.1(9)	$31/2^- \rightarrow 29/2^-$
7681.8	1907.2	w	$(35/2^-) \rightarrow 31/2^-$
8735.5	1053.6	w	$(39/2^-) \rightarrow (35/2^-)$
7527.5	1752.9	w	$(33/2^-) \rightarrow 31/2^-$
7762.4	234.9	b	$(35/2^-) \rightarrow (33/2^-)$
7064.0	1289.4	w	$(35/2^-) \rightarrow 31/2^-$
8137.3	1073.3	w	$(37/2^-) \rightarrow (35/2^-)$
8308.6	2534.0	w	$(35/2^-) \rightarrow 31/2^-$
2246.9	1305.2	1.6	$11/2^{(-)} \rightarrow 7/2^+$
2450.2	1098.1	9.8(1.1)	$(11/2^+) \rightarrow 9/2^+$
2493.4	43.0	c	$13/2^- \rightarrow (11/2^+)$
2493.4	463.9	2.9(1.2)	$13/2^- \rightarrow 13/2^+$
2575.1	291.3	7.4(5)	$(15/2^+) \rightarrow 17/2^+$
3702.2	1127.1	1.5(1.5)	$19/2^- \rightarrow (15/2^+)$
2999.5	715.4	e	$(15/2^-) \rightarrow 17/2^+$
3363.4	363.5	9.4(4)	$(19/2^+) \rightarrow (15/2^-)$
3363.4	824.6	3.9(7)	$(19/2^+) \rightarrow 21/2^+$
3986.1	622.6	w	$21/2^- \rightarrow (19/2^+)$
3363.1	787.9	3.5(1.7)	$(19/2^+) \rightarrow (15/2^+)$
4192.6	1655.1	4.0(1.2)	$23/2^- \rightarrow 21/2^+$

[a]Intensity could not be computed from singles as there exists another transition having similar energy in ^{96}Ru.
[b]Intensity could not be computed from singles as there exists another transition having similar energy in ^{92}Mo.
[c]From earlier work by P. Chowdhury *et al.* [9].
[d]Intensity includes the contribution from both the 255 keV transitions.
[e]Intensity could not be computed from singles due to contribution from unknown contaminant.
[w]Refers to extremely weak transitions whose intensity could not be computed from singles.

in coincidence, forming a sequence and that the transition 246 keV was reported to be not in coincidence with this sequence of transitions. What was found by us was that the 246 keV transition was in fact in coincidence with the 207 and 313 keV transitions. Figure 5 shows the spectrum gated by the 207 keV gamma ray. The 207 keV gamma ray was seen to be in coincidence with the 313 and 246 keV gamma rays. All these gamma rays were found to be members of the negative parity band. The same authors have reported 664 and 108 keV gamma rays, which we have not observed. In another earlier work by Chowdhury *et al.* [9] only one 255 keV gamma ray was reported to be in coincidence with the 1292 keV gamma ray. We confirm the finding of Goswami *et al.* [10] that the 1292 keV gamma ray was in coincidence with both the 255 keV gamma rays. Another main discrepancy with this work [9] is that we have found the 677 and 715 keV transitions to be in coincidence, while in Ref. [9] it has been reported that both these gamma rays were not in coincidence and that both feed the 1352 keV $9/2^+$ level. Further, Chowdhury *et al.* [9] have reported that the 255 and 715 keV transitions were not in coincidence, but we find that the 715 keV transition was in coincidence with one of the 255 keV transitions.

Chowdhury *et al.* [9] have reported that the 281 keV transition follows the 283 keV transition. Based on our data we have drawn the conclusion that the 283 keV transition is linked to the 281 keV transition via the 224 and 703 keV transitions, i.e., the sequence of gamma rays, 283-, 224-, 703-, 281 (all $M1$) keV was observed (Fig. 4). What tied down this sequence was the observation of in-band cross transitions with energies 508, 928, and 985 (all $E2$) keV. Figures 3 and 6 depict this situation. Further, we were fairly certain that the 313 and 283 keV transi-

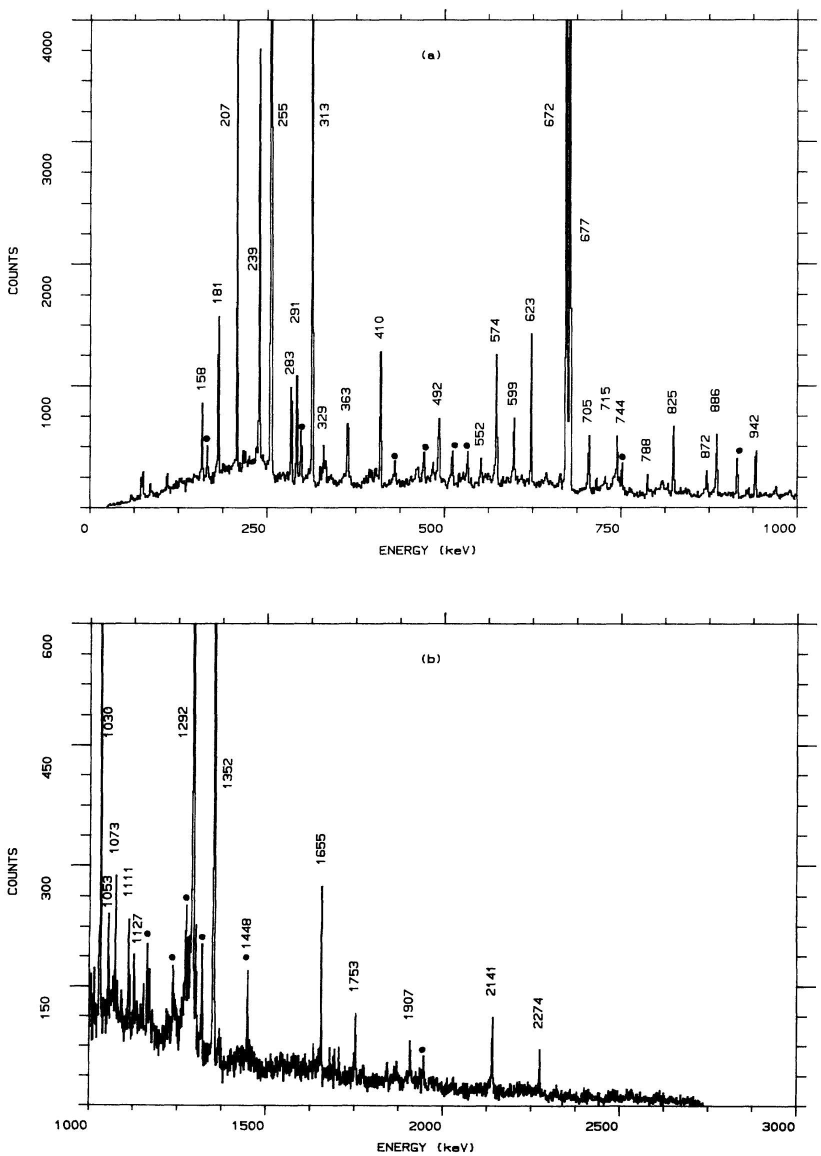

FIG. 1. γ-γ coincidence spectrum for ^{95}Ru with gate on the gamma transition 255 $(21/2^+ \rightarrow 17/2^+ \rightarrow 13/2^+)$ keV. All transition energies are marked within ± 1 keV. The transitions marked with a dot belong to some unknown contaminant.

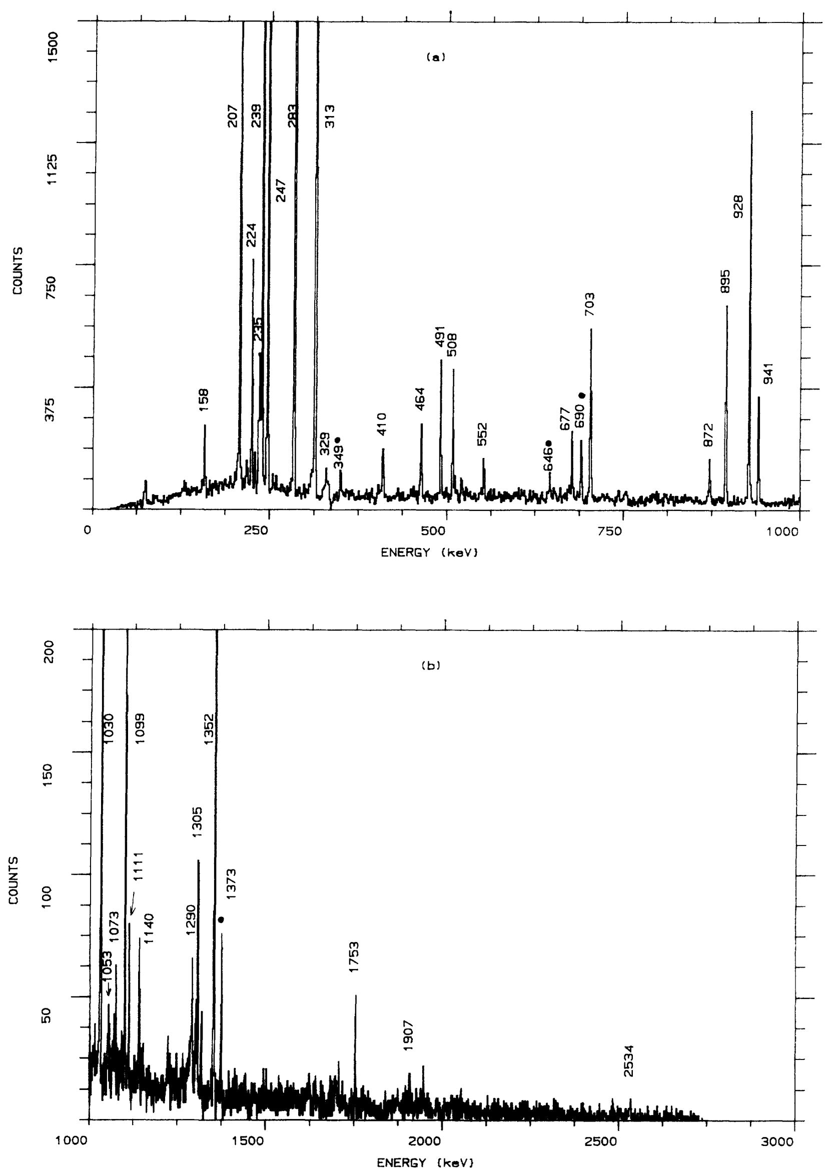

FIG. 2. γ-γ coincidence spectrum for ^{95}Ru with gate on the gamma transition 281 ($15/2^- \rightarrow 13/2^-$) keV. All transition energies are marked within ± 1 keV. The transitions marked with a dot belong to some unknown contaminant.

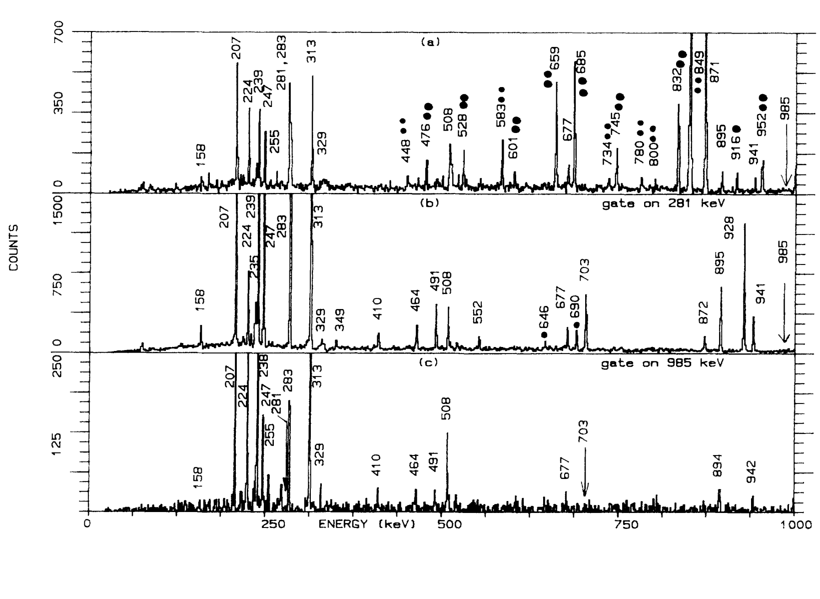

FIG. 3. (a),(b) Partial γ-γ coincidence spectra with gate on 703 ($17/2^- \rightarrow 15/2^-$) keV and 281 ($15/2^- \rightarrow 13/2^-$) keV transitions. The 985 ($17/2^- \rightarrow 13/2^-$) keV transition is absent. (c) Partial γ-γ coincidence spectra with gate on 985 keV transition. The 281 and 703 keV transitions are absent. All transition energies are marked within ± 1 keV. The transitions marked with a dot belong to some unknown contaminant. The transitions marked with two dots in spectrum (a) belong to ^{96}Ru. The observation of the 255 keV line in (a) may be due to the presence of a weak 255 keV γ line in the negative parity band. However, we have no conclusive evidence for this.

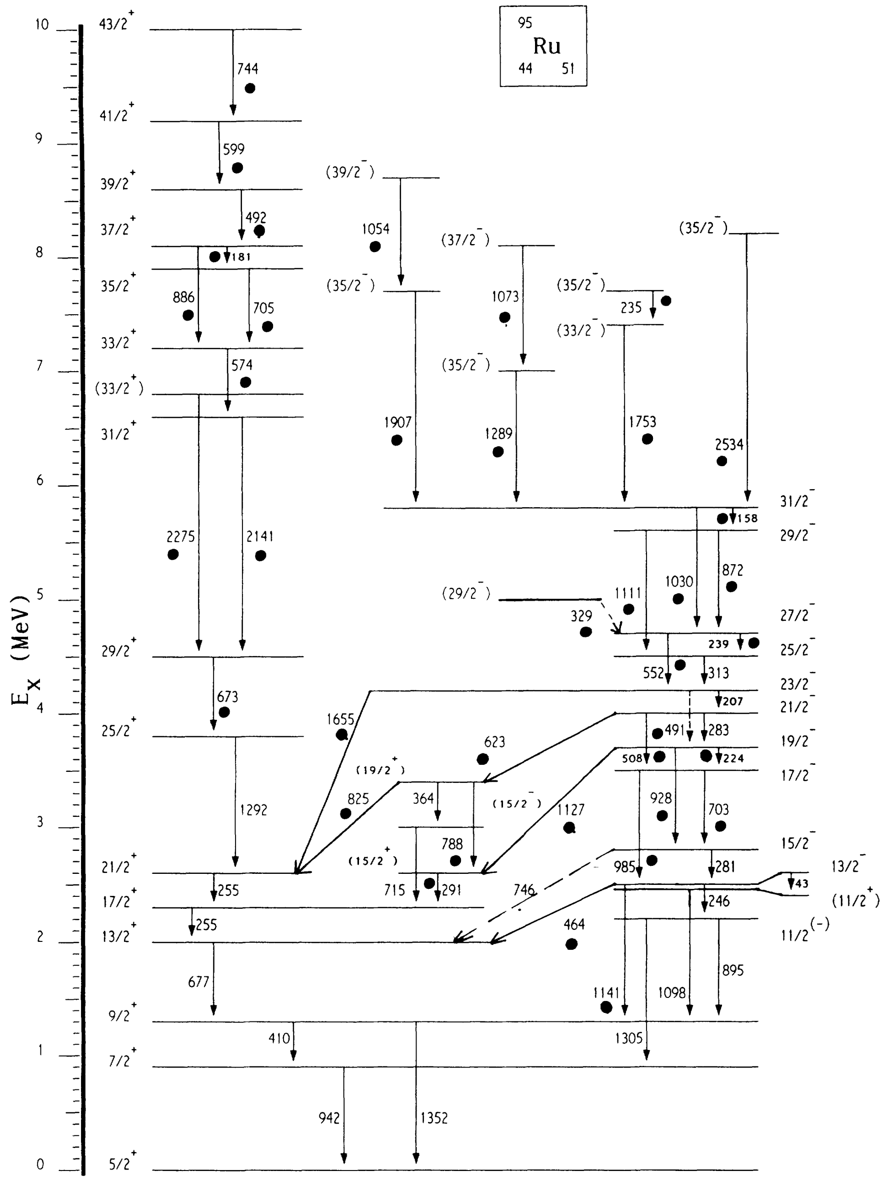

FIG. 4. Level scheme for ^{95}Ru showing excitation and gamma transition energies (in keV) for the levels populated in ^{64}Zn(^{35}Cl, 3pn)^{95}Ru reaction. Newly observed transitions are marked with a dot. The spin and parity assignments, given in parentheses, are tentative.

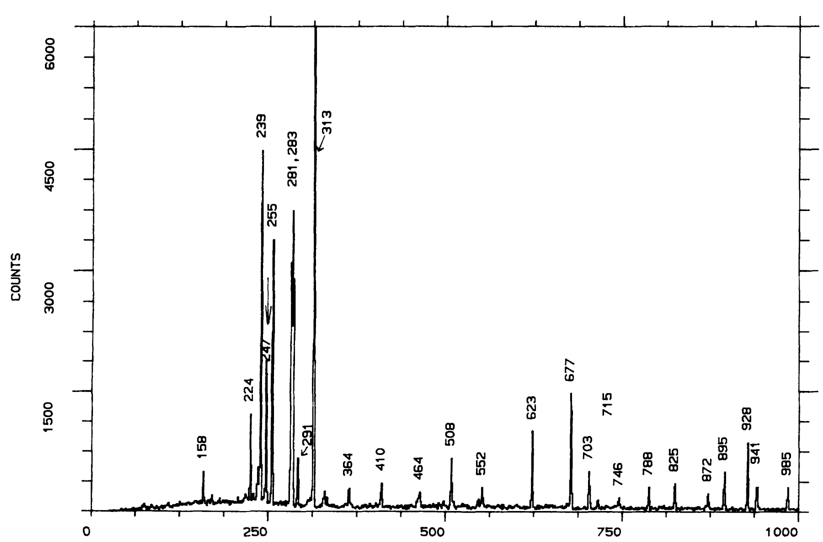

FIG. 5. γ-γ coincidence spectrum for ^{95}Ru with gate on the gamma transition 207 keV. Both 247 and 313 keV gamma rays are seen in coincidence with the 207 keV gamma ray. All transition energies are marked within $\pm$1 keV.

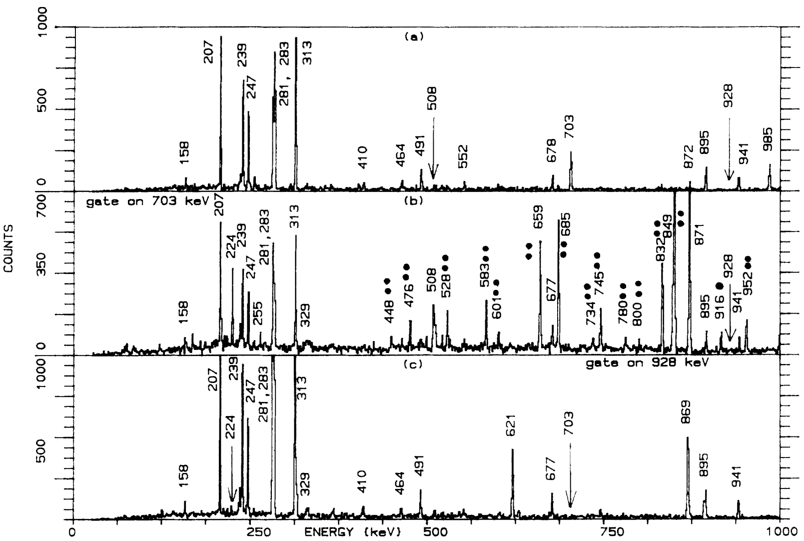

FIG. 6. (a),(b) γ-γ coincidence spectra with gate on 224 ($19/2^- \rightarrow 17/2^-$) and 703 ($17/2^- \rightarrow 15/2^-$) keV transitions. The 928 ($19/2^- \rightarrow 15/2^-$) keV transition is absent. (c) γ-γ coincidence spectra with gate on 928 keV transition. The 224 and 703 keV transitions are absent. All transition energies are marked within ± 1 keV. The transitions marked with a dot belong to some unknown contaminant and those marked with double dots in (a) belong to ^{96}Ru. Also see caption for Fig. 3.

tions were in-band transitions in the negative parity band and so assigned them a multipolarity $M1$. In Ref. [9] these transitions were tentatively assigned $E1$ character. The 246 keV transition was also assigned tentatively an $E1$ character in Ref. [9]. This gamma ray being at the bottom of the negative parity band its parity assignment was uncertain, and so it is only tentatively indicated in brackets. In view of this tentative assignment of multipolarity for the 246 keV transition, the second 11/2 state at 2450 keV excitation energy, where the 43 keV transition ends [9], is tentatively given a positive parity. The spin parity assignment is again shown in brackets.

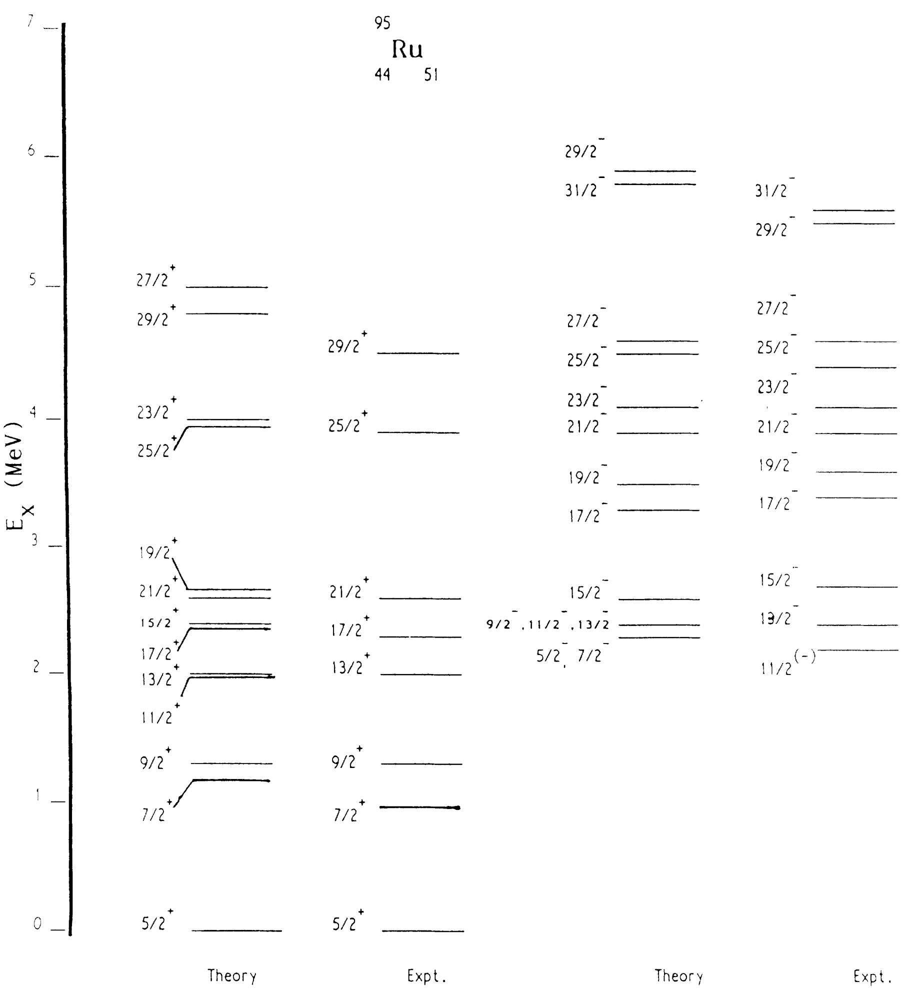

FIG. 7. Comparison of the observed states in ^{95}Ru with spherical shell model calculations with the 6 protons in $(2p_{1/2}, 1g_{9/2})$ and one neutron in $(3s_{1/2}, 2d_{5/2})$ orbits outside the ^{88}Sr core. No comparison is made for the levels that have a tentative spin and parity assignment.

Finally a point worth mentioning is that the intensity in the positive parity band abruptly drops (Table I) by a factor of about 4 above the $29/2^+$ level. We have no definite reason to give for this observation though it is quite possible that the intensity might have gone in other yet to be identified pathways. In view of such a number of differences in the experimental observations for even the low lying states, our level scheme of ^{95}Ru (Fig. 4) is substantially different from the earlier work [9,10].

IV. THEORETICAL DISCUSSION

The spherical shell model calculations using the code OXBASH [12] were carried out for the nucleus ^{95}Ru. The model space used in these calculations had ^{88}Sr at the inert core with the valence protons occupying the $2p_{1/2}$ and $1g_{9/2}$ orbits and the valence neutron occupying the $2d_{5/2}$ and $3s_{1/2}$ orbits. The two body matrix elements were taken from Ref. [13]. However, in this configuration space the maximum angular momenta possible with six protons in the $(2p_{1/2}, 1g_{9/2})$, and one neutron in the $(2d_{5/2}, 3s_{1/2})$ orbits were $29/2^+$ and $31/2^-$. Up to these moderately high spins there was a good agreement between the experimental data and the shell model calculations. Figure 7 shows this comparison. In this figure we have not shown those levels that were given only a tentative spin parity assignment.

In the present work the high spin states have been established experimentally up to spins $43/2^+$ and $39/2^-$ for ^{95}Ru. In order to generate these high spin states we have tried coupling of a $2d_{5/2}$ valence neutron to an excited ^{94}Ru core [4,14,15]. With protons and neutrons oc-

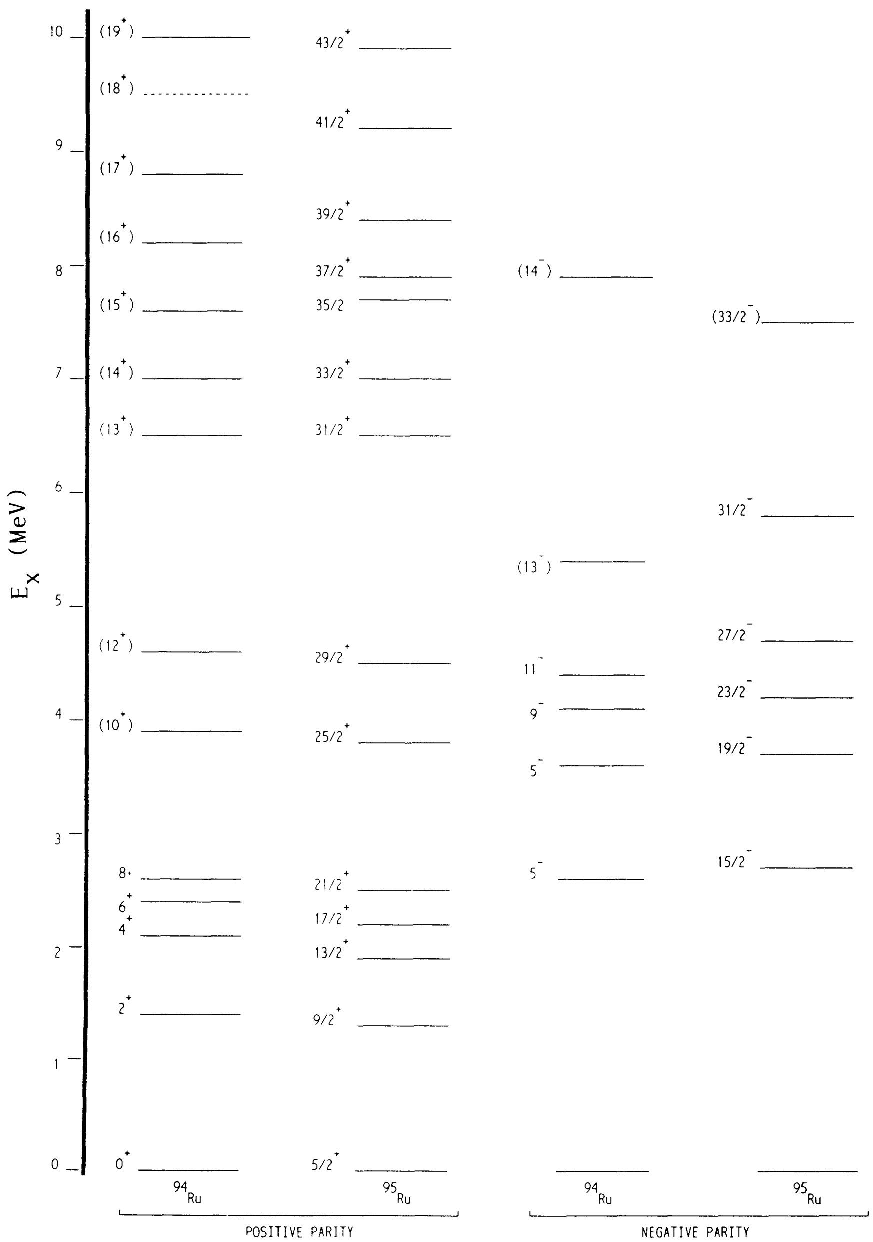

FIG. 8. Comparison of the observed spectra of ^{94}Ru and ^{95}Ru.

cupying different configurations spaces, a weak coupling approximation appeared to be a reasonably valid approach. This attempt turned out to be quite successful as can be seen from Fig. 8. The observed high spin states in ^{95}Ru, thus were adequately represented by this weak coupling scheme ($^{94}\mathrm{Ru}\otimes\nu 2d_{5/2}$).

The excitation of a neutron from the $N=50$ closed core to the $2d_{5/2}$ level in the next shell is another plausible mechanism for generating the observed higher angular momentum states. Unfortunately due to the computational memory limitations we could not explore this mechanism.

Finally there are two experimental observations that have interesting theoretical implications worth mentioning here. The top three transitions in the positive parity band, 492, 599, and 744 keV have somewhat similar energies. A similar feature had been reported by us for the top three transitions in the positive parity band in the $N=50$ nucleus ^{93}Tc [3]. This appears to be an indication of collective behavior of the nucleus. However, more experimental work is needed to understand this aspect.

Another feature is the striking similarity between the level structure above $31/2^-$ in ^{95}Ru and above 9^- in ^{96}Ru [16]. In the case of ^{95}Ru it occurs at an excitation energy around 5.8 MeV, while in the case of ^{96}Ru it occurs at an excitation energy around 4 MeV. This probably indicates the importance of the many particle correlations.

V. CONCLUSIONS

The level scheme of ^{95}Ru has been substantially extended up to a spin $43/2^+$ in the positive parity band and $39/2^-$ in the negative parity band. Forty new transitions were found and placed in the level scheme. Several discrepancies with the earlier work were found.

Using ^{88}Sr core with the six protons occupying the $(2p_{1/2}, 1g_{9/2})$ configuration space and the one neutron occupying the $(2d_{5/2}, 3s_{1/2})$ configuration space, states up to spins of $29/2^+$ and $31/2^-$ could be well reproduced in ^{95}Ru on the basis of the spherical shell model calculations.

The weak coupling of a valence $2d_{5/2}$ neutron to the excited ^{94}Ru core could generate reasonably well, the observed spectrum of ^{95}Ru including the high spin states. A more rigorous approach to understanding the nature of the high spin states in ^{95}Ru is to consider the excitation of a neutron from the closed $N=50$ core to the next shell.

The deformed structure seen in $Z=51$ nucleus, ^{117}Sb were not observed in the $N=51$ nucleus ^{95}Ru. However, there is a regularity at the top of the positive parity band, which appears to be an indication of collective behavior. A similar feature was observed in our earlier work on high spin states in the $N=50$ nucleus ^{93}Tc.

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