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Level schemes of ^{98}Pd and ^{96}Ru

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Levels of the ground-state cascade of ^{98}Pd up to $J^\pi=16^+$ were established by means of the reaction ^{70}Ge(^{32}S,2p2nγ)^{98}Pd with $E_{\rm lab}=120$ MeV. The ^{96}Ru(^{16}O,^{14}C)^{98}Pd reaction was used to aid in the nuclidic identification of the observed γ-ray transitions. We compare the excitation energies of the new states of ^{98}Pd with states of the $N=52$ isotone ^{96}Ru, which were populated using four distinct reactions. No evidence has been found for the existence of collective four-particle—two-hole states involving the excitation of a pair of $g_{9/2}$ neutrons across the $N=50$ shell closure. The level schemes are discussed in terms of the nuclear shell model while the empirical ratios of energies are presented from the viewpoint of the variable moment of inertia model.

INTRODUCTION

The present study of high-spin states of ^{98}Pd is a continuation of an effort[1] to study the level schemes of increasingly neutron-deficient even-A Pd nuclides which approach $N=50$ neutrons from above. One goal was to establish the limits of validity of the extended variable moment of inertia (VMI) model[2(a),(b),(d)] near the lowest value of R_4 $(=E_{4^+}/E_{2^+})=1.82$ for which the model applies. Deviations at and above the 6^+ level in nearby ^{100}Pd have recently been shown[2(c)] to be due to the fact that this nuclide is pseudomagic: ^{100}Pd is an isobar of doubly magic ^{100}Sn (it contains four proton holes in the $Z=50$ shell and four neutrons above $N=50$).

We were aided in this effort by the population, by means of several distinct projectile-target combinations, of high-spin states in the $N=52$ isotone ^{96}Ru. The yrast states of ^{96}Ru and ^{98}Pd up to $J^\pi=6^+$ were expected to have similar excitation energies in view of the similarity previously observed between ^{98}Ru and ^{100}Pd, and also between ^{100}Ru and ^{102}Pd, as shown in Fig. 1. This figure summarizes the known yrast levels in the even-A nuclides with either 52, 54, or 56 neutrons. Figure 1 also exhibits a transition (for the even-A Ru and Pd nuclides) from the regular collective bands found for the $N=54$ and 56 systems to the bands found in ^{96}Ru ($N=52$) which exhibit irregular energy spacings characteristic of shell-model effects. A comparison of the level energies of ^{98}Pd and ^{96}Ru would be expected to display those features due to the number of protons differing by two. On the other hand, those features which the two level schemes have in common could be attributed to the presence of two valence neutrons outside an inert $N=50$ core. For example, in the context of the shell model, one expects to observe a relatively small $6^+\rightarrow4^+$ transition energy in both nuclides due to the presence of two neutrons in either the $\nu g^2_{7/2}$ or $\nu d_{5/2}g_{7/2}$ configurations.

A second goal was to search for evidence of collective four-particle—two-hole (4p-2h) states related to the excitation of a pair of $g_{9/2}$ neutrons across the $N=50$ shell closure. These states would be analogous to collective proton excitation states recently found[3,4] in several Sn(2p-2h), Sb(2p-1h), Te(4p-2h), and I(4p-1h) nuclides. Specifically, it is expected that there exist states in ^{96}Ru and ^{98}Pd which are members of a $\Delta J=2$ positive parity band built upon an excited $J^\pi=0^+$ state; this state is analogous to states recently reported for several $Z=52$ even-A Te nuclides.[4] Whether or not electric quadrupole ($E2$) transitions between these 4p-2h states in ^{96}Ru or ^{98}Pd can actually be observed depends, however, on whether the states occur at a low enough excitation energy to be significantly populated by the fusion-evaporation process. In this regard, the present situation ($N=52$) is not as favorable as is the $Z=52$ case for reasons which will be discussed below.

Prior to the present work, the excited states of ^{98}Pd had not been studied. A first preliminary report[5] assigned a γ-ray cascade to ^{98}Pd on the basis of observed γ-ray excitation functions produced by ^{12}C+^{90}Zr and ^{16}O+^{86}Sr. With the optimum beam energies of 71 and 85 MeV for the ^{12}C and ^{16}O beams, respectively, the two most intense members of this cascade were γ841.1 and γ725.6. Further work showed, however, that the cascade could also be produced promptly by a ^{10}B+^{92}Zr bombardment.[6] Therefore, the cascade could only be assigned to a nuclide with $Z\leq45$ (probably ^{98}Rh) and not to ^{98}Pd. However, subsequent work utilizing a ^{32}S+^{70}Ge bombardment allowed us to assign[7] a new γ-ray cascade to ^{98}Pd. This latter assignment has been confirmed by two separate experiments. In one experiment, using the ^{96}Ru (^{16}O,^{14}C)^{98}Pd reaction,[7,8] the energy spacings between the $J^\pi=0^+$, 2^+, and 4^+ states of ^{98}Pd were deduced from the ^{14}C spectrum produced (see Fig. 6 which will be discussed later). In the other experiment,[9] the γ-ray transitions in ^{98}Pd were observed following the EC-β^+ decay of 44 s ^{98}Ag. In both experiments, the assigned transitions are in agreement with the second preliminary report[7] of this work. Most recently, Behar *et al.*[10] confirmed the lower-spin states of ^{98}Pd up to $J^\pi=12^+$.

The low-spin states of ^{96}Ru following the EC-β^+ decay of ^{96}Rh, ^{96}Rh^m have been studied by Doron and Blann,[11] while the high-spin states up to $J^\pi=12^+$ were deduced by Lederer *et al.*[12] using the ^{94}Mo(α,2nγ)^{96}Ru reaction. Most recently, high-spin states up to $J^\pi=12^+$ were reported by Walkiewicz *et al.*[13] from the

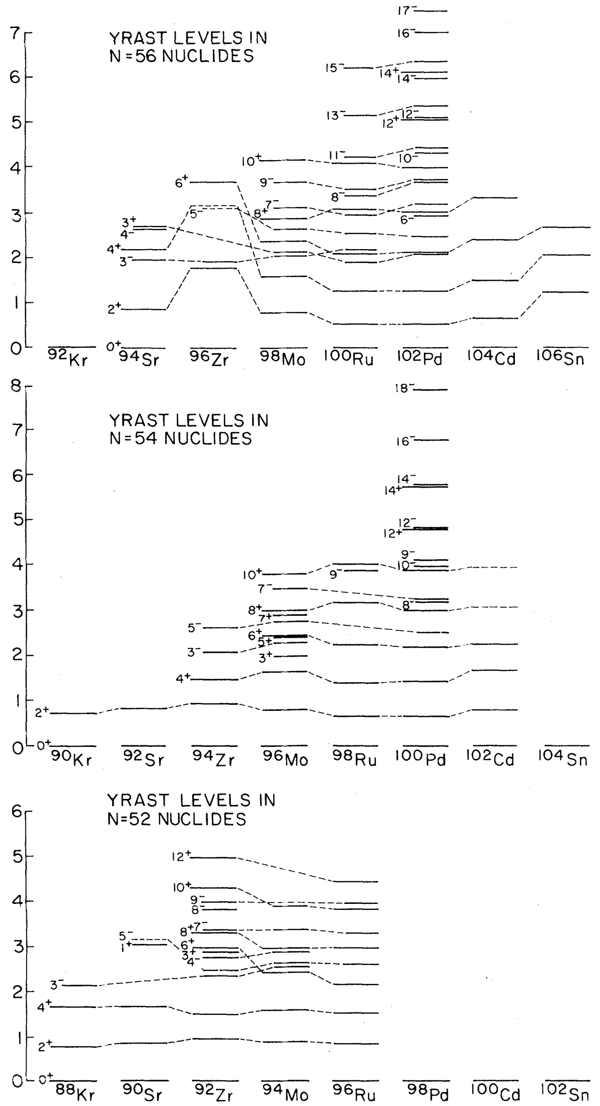

FIG. 1. Previously known yrast levels for the even-A nuclides with $N=56$ (top), $N=54$, (middle), and $N=52$ (bottom) neutrons. The similarity in excitation energy for the $J^{\pi}=2^{+}$ and 4^{+} levels for each of the isotonic pairs ^{100}Ru-^{102}Pd and ^{98}Ru-^{100}Pd suggested that the excitation energies of these levels of ^{98}Pd would be similar to those of ^{96}Ru as discussed in the text.

^{93}Nb(^{6}Li,3nγ)^{96}Ru reaction. They also studied in detail the EC-β^{+} decay of ^{96}Rh,^{96}Rh^{m} to ^{96}Ru. The present results for ^{96}Ru are in agreement with these three previous studies, as will be shown below; in addition, new states of ^{96}Ru up to $J^{\pi}=18^{+}$ and 12^{-} are deduced.

EXPERIMENTS

The reaction ^{70}Ge(^{32}S,2p2nγ)^{98}Pd with $E_{\rm lab}=120$ MeV was utilized to populate high-spin states of ^{98}Pd using ions produced by the Brookhaven Tandem Van de Graaff facility. The ^{70}Ge targets of 500–800 μg/cm^{2} were enriched to 85% and evaporated onto thick tantalum backings. The use of this reaction to search for the high-spin states of ^{98}Pd was suggested by a study[14] of ^{32}S+^{70}Ge with $E_{\rm lab}=132$ MeV utilizing a magnetic spectrometer to record the evaporation residues. This study showed that a significant amount of the evaporation residues, namely 21 ± 1 %, have mass $A=98$. This observation suggested the use of this reaction for studying high-spin states of ^{98}Pd by γ-ray spectroscopy. The states of ^{96}Ru were populated by means of four reactions: (1) ^{90}Zr(^{12}C,α2nγ)^{96}Ru with $E_{\rm lab}=71$ MeV; (2) ^{66}Zn(^{35}Cl,3p2nγ)^{96}Ru with $E_{\rm lab}=170$ MeV; (3) ^{70}Ge(^{32}S,α2pγ)^{96}Ru with $E_{\rm lab}=120$ MeV; and (4) ^{60}Ni(^{40}Ca,4pγ)^{96}Ru with $E_{\rm lab}=140$ MeV (Ref. 15). The self-supporting ^{90}Zr target was enriched to 98% and was 10 mg/cm^{2} thick, while the ^{66}Zn target (enriched to 98%) consisted of 1.4 mg/cm^{2} evaporated onto a thick tantalum backing. To produce the ^{60}Ni target (enriched to 99%), 1 mg/cm^{2} was evaporated onto a 20 mg/cm^{2} thick layer of lead. For each of these reactions, γ-ray excitation functions, γ-ray angular distributions, and γ-γ coincidences were recorded, except for ^{40}Ca+^{60}Ni, for which the γ-ray angular distributions were not measured. The coincidence data were event-mode recorded onto magnetic tape for subsequent playback and analysis.

Figure 2 shows a γ-ray singles spectrum produced by ^{32}S+^{70}Ge with $E_{\rm lab}=130$ MeV and recorded by using an 85 cm^{3} Ge(Li) detector. The simultaneous production of several fusion-evaporation products is evident. A γ-γ coincidence experiment revealed that the moderately in-

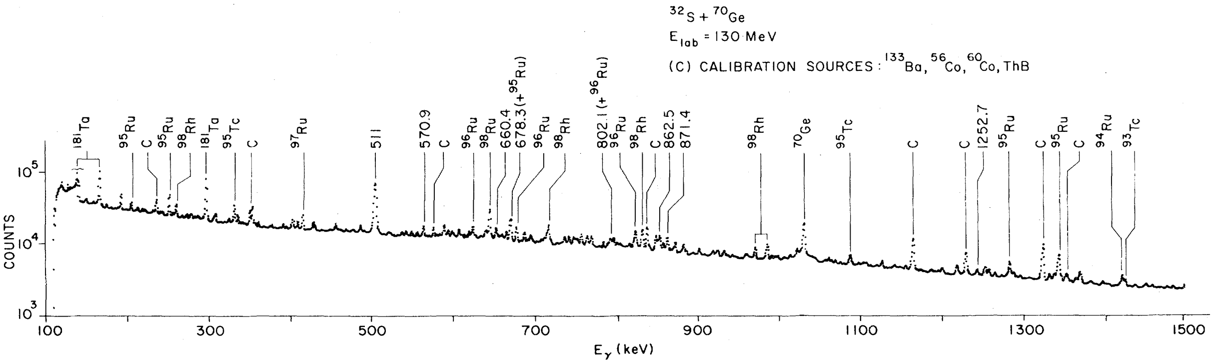

FIG. 2. A Ge(Li) singles spectrum produced by ^{32}S+^{70}Ge with $E_{\rm lab}=130$ MeV. The transitions assigned to ^{98}Pd are labeled with their energies (in keV). Other large peaks are labeled by nuclide, while several peaks, labeled (C), are due to radioactive calibration sources.

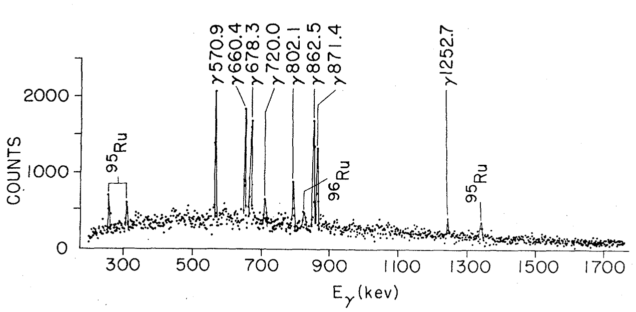

FIG. 3. Sum spectrum of background-subtracted γ-ray gates for ^{98}Pd transitions produced by ^{32}S+^{70}Ge with $E_{\mathrm{lab}}=120$ MeV.

tense 862.5 keV transition is coincident with the 678.3 keV one. These two transitions were observed to be the most intense members of a coincident cascade of eight transitions. The spectrum formed by summing six Compton-background subtracted gates set on photopeaks from one Ge(Li) detector is displayed in Fig. 3. This γ-ray cascade is arranged in order of observed relative intensity and displayed on the left-hand side of Fig. 4.

As mentioned above, the γ rays produced by ^{10}B+^{92}Zr with $E_{\mathrm{lab}}=40$, 45, and 55 MeV were recorded in order to check the assignment to ^{98}Pd for the cascade displayed in Fig. 4. The Ge(Li) singles spectrum recorded with $E_{\mathrm{lab}}=55$ MeV appears in Fig. 5. There is no evidence in Fig. 5 for the transitions displayed in Fig. 4, in agreement with their assignment to ^{98}Pd. However, the γ rays in a cascade previously assigned[5] to ^{98}Pd are evident in Fig. 5, indicating that these latter γ rays must instead occur in a nuclide with $Z \lesssim 45$, as has also been pointed out previously.[6]

An additional check on the assignment to ^{98}Pd was obtained from a separate experiment[8] to measure the mass excesses of the three nuclides ^{98,99,100}Pd. In that experiment, the Brookhaven quadrupole-dipole-dipole-dipole magnetic spectrometer was utilized to record the ^{14}C spectrum produced at $\theta_{\mathrm{lab}}=40°$ by the reaction ^{96}Ru(^{16}O,^{14}C)^{98}Pd with $E_{\mathrm{lab}}=70$ MeV as shown in Fig. 6.

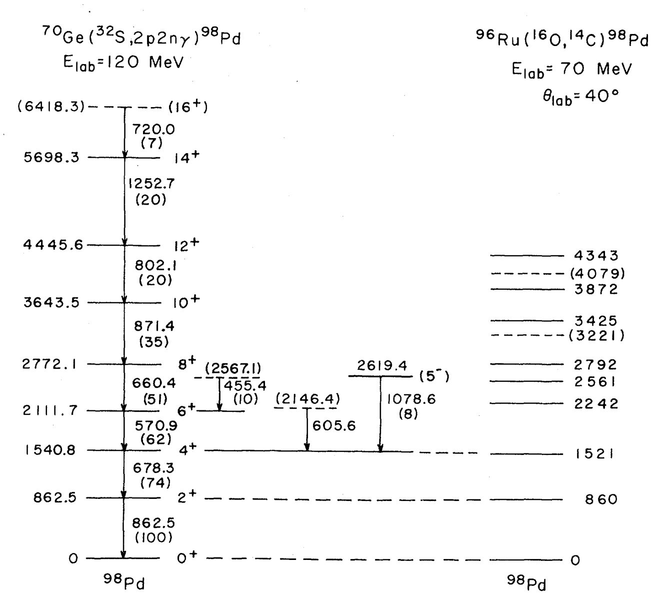

FIG. 4. Proposed ^{98}Pd level scheme. The levels shown on the left-hand side are deduced by γ-ray spectroscopic methods while those on the right-hand side were deduced from particle spectroscopy (Ref. 8). The uncertainty in the excitation energy of each of these latter levels is ±17 keV.

The Q values obtained from this spectrum are listed in Table II of Ref. 8. The levels of ^{98}Pd deduced from the Q values are shown on the right-hand side of Fig. 4. These levels are expected to be partly nonyrast levels in contrast to those obtained from γ-ray spectroscopy. The uncertainty in the excitation energies deduced from the ^{14}C spectrum is ±17 keV. To this degree of accuracy, the excitation energies of the 2^+ and 4^+ levels of ^{98}Pd are in reasonable agreement with those deduced from the γ-ray data as summarized in Fig. 4.

In a separate experiment, the γ-ray angular distributions produced by ^{32}S+^{70}Ge were recorded with $E_{\mathrm{lab}}=130$ MeV. Under computer control, a Ge(Li) detec-

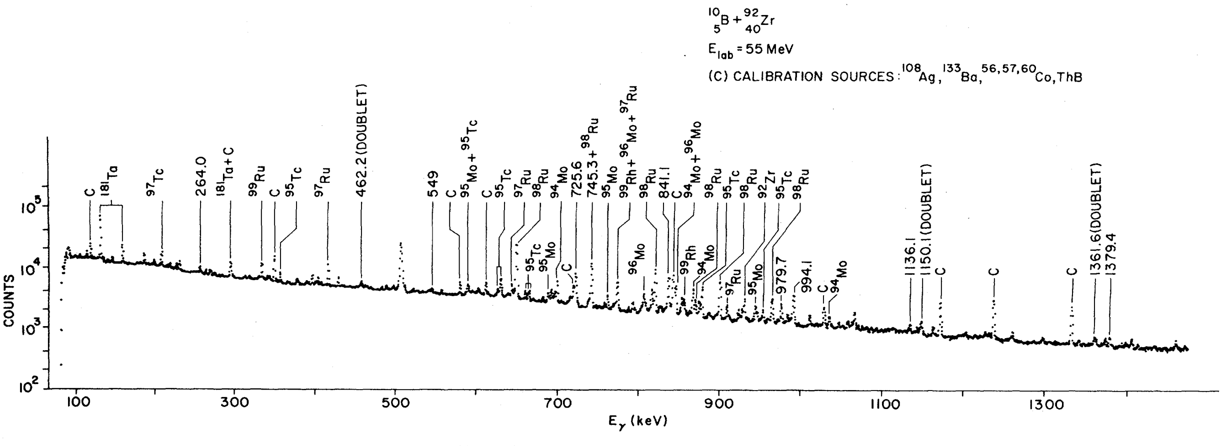

FIG. 5. A Ge(Li) singles spectrum produced by ^{10}B+^{92}Zr with $E_{\mathrm{lab}}=55$ MeV. The strongest transitions of a cascade previously assigned to ^{98}Pd are labeled with their energies (in keV). This spectrum is evidence that this assignment was incorrect and that, therefore, the cascade must be assigned to a nuclide with $Z \leq 45$ (probably ^{98}Rh). The transitions presently assigned to ^{98}Pd are not seen in this spectrum, in agreement with this assignment.

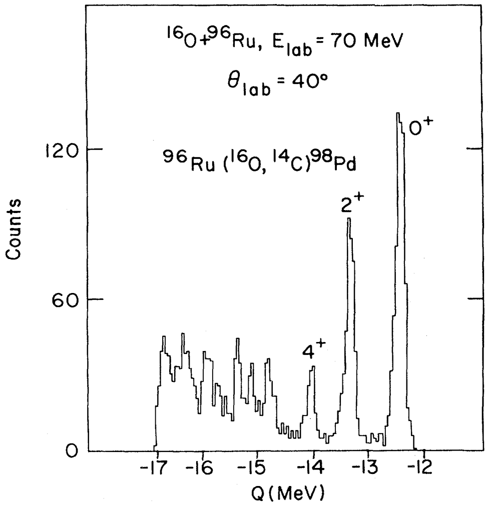

FIG. 6. The ^{14}C position spectrum produced at the focal plane of a quadrupole-dipole-dipole-dipole magnetic spectrometer by the ^{96}Ru(^{16}O,^{14}C)^{98}Pd reaction with $E_{\text{lab}}=70$ MeV. The abscissa is labeled by the Q value calibrated by utilizing elastic scattering as discussed in detail in Ref. 8.

tor was positioned successively at each of eight angles ranging from 60° to 162° with respect to the beam direction. Two methods of normalization were utilized and found to agree to within 2%: (1) the digital output of a beam current integrator connected to the beam dump was stored in a computer, and (2) a monitor Ge(Li) detector, positioned at 90° and on the other side of the beam line, was used to count γ rays with $E_\gamma > 600$ keV. The results of the γ-ray angular distribution experiment will be presented below.

For the ^{35}Cl+^{66}Zn γ-γ coincidence experiment, Fig. 7 shows the sum spectrum of several background-subtracted gates set on transitions of ^{96}Ru. The level scheme of ^{96}Ru, which has been deduced from these and other data, is shown in Fig. 8 and will be discussed in the following.

RESULTS

In order to obtain information about the multipolarity of each transition of ^{98}Pd and ^{96}Ru, the formula

$$W(\theta)=A_0+A_2P_2(\theta)+A_4P_4(\theta) \tag{1}$$

was fit to the observed intensity function $W(\theta)$, where θ is the angle of the detector measured with respect to the beam direction; A_0, A_2, and A_4 are adjustable parameters; while P_2 and P_4 are Legendre polynomials. The empirical intensity $W(\theta)$ is obtained for each transition by subtracting the Compton background from the intensity under the photopeak. The results of the fitting procedure are listed in Table I for ^{98}Pd and in Table II for ^{96}Ru. In both tables, a slight correction was made to the A_0, A_2/A_0, and A_4/A_0 values for the finite solid angle subtended by the Ge(Li) detector. The values of A_0 obtained were also corrected for the efficiency of the Ge(Li) detector and normalized to the $2^+\rightarrow0^+$ transition for each nuclide to obtain the relative γ-ray intensities. Table II also lists angular distribution results for the ^{96}Ru transitions obtained from the ^{66}Zn(^{35}Cl,3p2nγ)^{96}Ru reaction with $E_{\text{lab}}=165$ MeV and the ^{90}Zr(^{12}C,α,2nγ)^{96}Ru reaction with $E_{\text{lab}}=71$ MeV.

For ^{98}Pd, the spin-parity assignments up to $J^\pi=8^+$ seem straightforward. These four transitions have also been observed in a study[9] of delayed γ rays (associated with $A=98$) produced by ^{14}N+^{92}Mo with $E_{\text{lab}}=110$ and 125 MeV. Using the LISOL mass separator, Huyse *et al.*[9] assigned these four transitions to the ground state cascade of ^{98}Pd as mentioned above. The relative intensities of the four transitions observed by Huyse *et al.* following the EC-β^+ decay of ^{98}Ag are consistent with the ordering shown in Fig. 4. For the $10^+\rightarrow8^+$ and $16^+\rightarrow14^+$ transitions, the assignments are based on systematics (i.e., ^{96}Ru), while γ802.1 and γ1252.7 can be more definitely assigned as stretched $E2$ transitions.

For ^{96}Ru, the spin-parity assignments seem to be straightforward up through the $J^\pi=10^+$ level as listed in

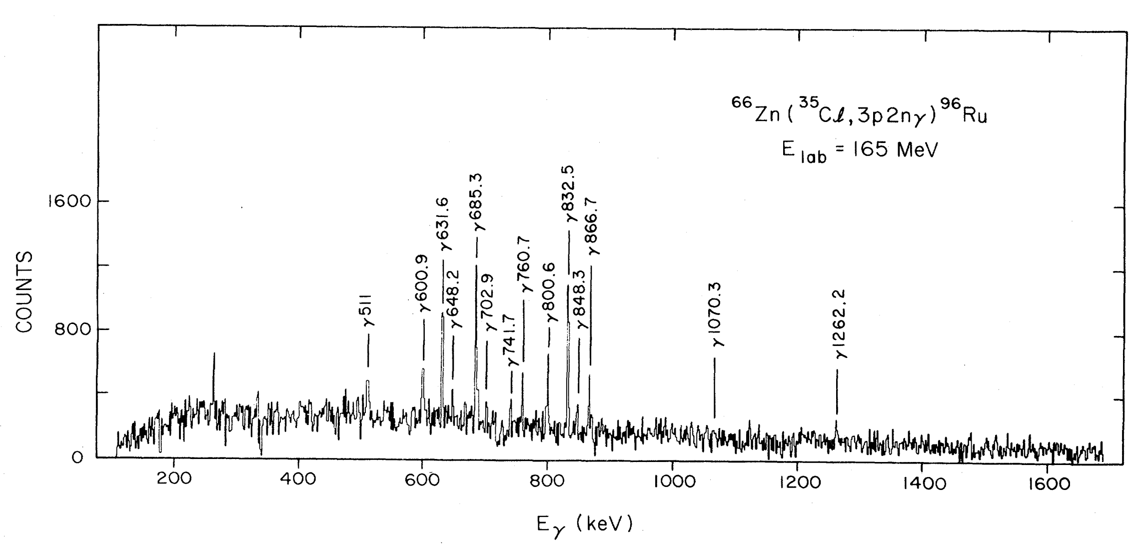

FIG. 7. Sum spectrum of background-subtracted γ-ray gates for ^{96}Ru produced by ^{35}Cl+^{66}Zn with $E_{\text{lab}}=165$ MeV. The ^{96}Ru transitions are labeled with their energies (in keV).

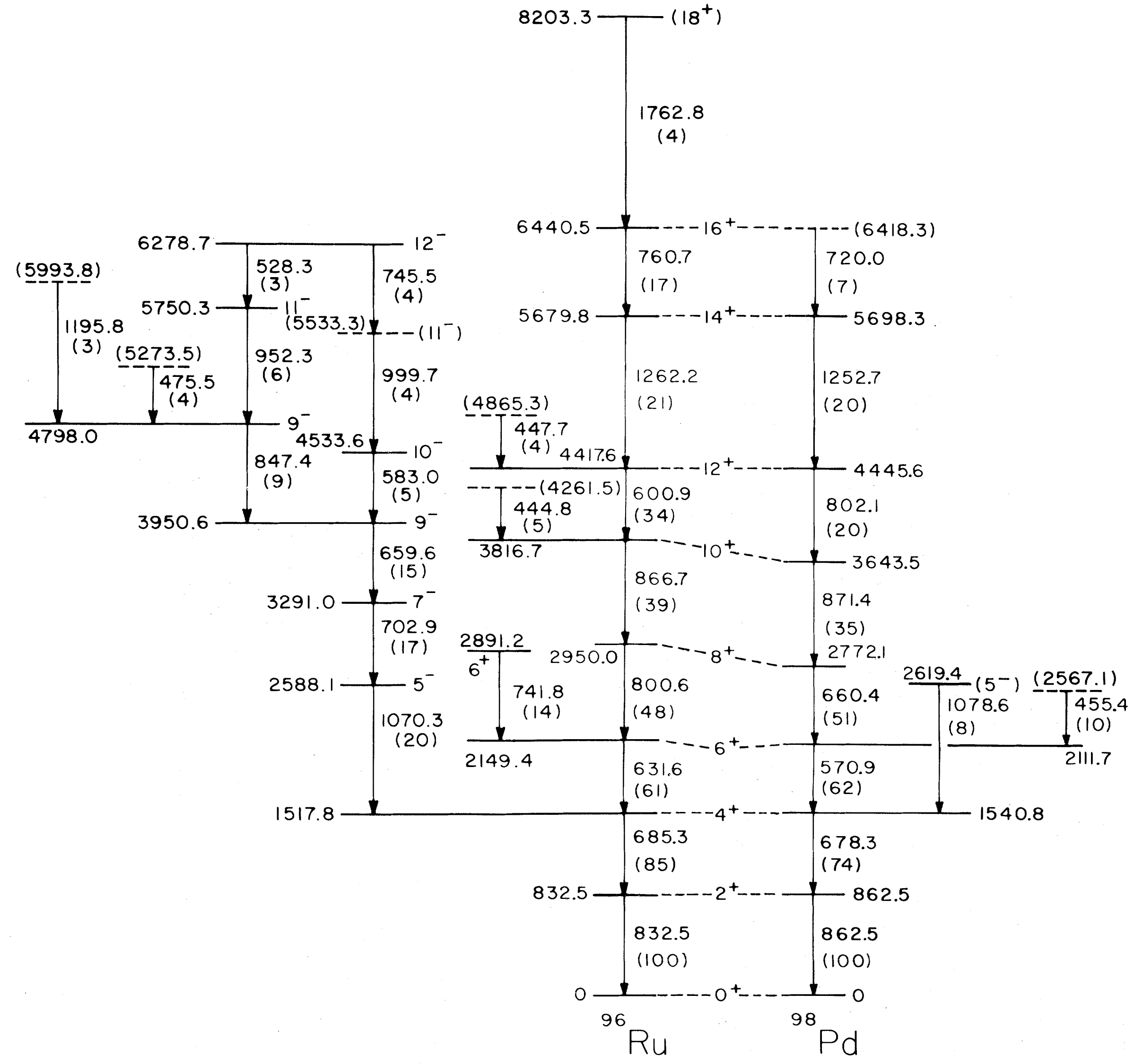

FIG. 8. Proposed ^{96}Ru and ^{98}Pd level schemes. The lower spin levels in ^{96}Ru are in agreement with a previous (α,2nγ) study (Ref. 12) and a (^{6}Li,3nγ) study (Ref. 13).

Table II and displayed in Fig. 8. For γ600.9, however, the A_2/A_0 values are consistently smaller than for the $10^+ \rightarrow 8^+$ transition immediately following in the ^{96}Ru level scheme. On the other hand, in the previous ^{94}Mo(α,2nγ)^{96}Ru study,[12] this transition was observed with a large positive A_2/A_0 value and assigned to be a $12^+ \rightarrow 10^+$ transition. Therefore, we support this assignment as shown in Fig. 8. The 1262.2-, 760.7-, and 1762.8-keV transitions also appear to be stretched quadrupole transitions. Several new levels of ^{96}Ru were best inferred from a ^{40}Ca+^{60}Ni γ-γ coincidence experiment, with $E_{\mathrm{lab}}=140$ MeV, intended primarily to study nearby ^{96}Pd (Ref. 15). The lower-spin negative parity levels listed in Table II up to $J^{\pi}=9^-$ and the positive parity levels up to $J^{\pi}=12^+$ were also deduced by Lederer *et al.*[12] and by Walkiewicz *et al.*[13] and are in agreement with the present assignments. The 583.0 keV transition in ^{96}Ru appears to be a $10^- \rightarrow 9^-$ transition. The angular distribution data for this transition listed in Table II are consistent with a stretched dipole assignment. Moreover, the parity of the 4533.6 keV level appears to be odd since if instead it were even, a 716.9 keV transition to the yrast 10^+ level would be expected, in contrast to experiment. The angular distribution results for γ847.4 are characteristic of a $\Delta J=0$ quadrupole transition because of the large negative A_4/A_0 value listed in Table II. This leads to a $J^{\pi}=9^-$ assignment for the 4798.0 keV level in ^{96}Ru. Analysis of the data listed in Table II leads to assignments of odd parity for the other levels shown in Fig. 8. The 999.7 keV $(11^-) \rightarrow 10^-$ transition has been placed differently from that proposed by Walkiewicz *et al.*,[13] who assigned a 1000.1 keV transition from the 3950.6- to the 2950.0-keV

TABLE I. Transitions in ^{98}Pd produced by 130 MeV ^{32}S+^{70}Ge. The relative transition intensities have been corrected for the efficiency of the Ge(Li) detector. The A_2/A_0 and A_4/A_0 values have undergone the slight corrections necessary to take the finite solid angle of the detector into account.

E_γ (keV)	$I_\gamma^{\rm rel}$	A_2/A_0	A_4/A_0	Assignment
862.48±0.14	≡100.0 ±1.0	+0.282±0.015	−0.099±0.022	$2^+ \to 0^+$
678.3 ±0.6	73.5 ±4.1	a	a	$4^+ \to 2^+$
570.91±0.10	61.9 ±0.7	+0.326±0.020	−0.096±0.029	$6^+ \to 4^+$
660.41±0.24	51.0 ±2.1	+0.332±0.026[b]	−0.116±0.038[b]	$8^+ \to 6^+$
871.36±0.14	34.7 ±1.7	c	c	$10^+ \to 8^+$
802.1 ±0.8	19.4 ±2.5	+0.324±0.039[d]	−0.081±0.057[d]	$12^+ \to 10^+$
1252.69±0.14	20.33±0.39	+0.237±0.041	−0.171±0.060	$14^+ \to 12^+$
720.0 ±0.5	7.3 ±1.7	e	e	$(16^+ \to 14^+)$
455.38±0.29	9.7 ±0.5	+0.11 ±0.11	−0.41 ±0.17	$\to 6^+$
605.65±0.14		f	f	$\to 4^+$
1078.59±0.19	8.0 ±0.8	−0.11 ±0.20	−0.03 ±0.30	$(5^-) \to 4^+$

[a] Unresolved from γ677.6 in ^{95}Ru.
[b] Unresolved from γ663.0 in ^{98}Rh, γ659.6 in ^{96}Ru, and γ661.0 in ^{95}Ru.
[c] Unresolved from γ871.10 in ^{94}Mo.
[d] Unresolved from γ800.6 in ^{96}Ru.
[e] Unresolved from γ719.4 in ^{102}Pd (from ^{74}Ge target contamination).
[f] Unresolved from another transition.

level. Finally, the ordering of the 745.5- and 999.7-keV transitions is tentative. Therefore, the 5533.3 keV level shown in Fig. 8 has been dashed.

DISCUSSION

It is apparent in Fig. 8 that the yrast $J^\pi=6^+$ states of both nuclides are relatively low lying. This is related to the presence of the $\nu d_{5/2}g_{7/2}$ and $\nu g_{7/2}^2$ configurations, although the $6^+ \to 4^+$ transition energies are not exactly those expected for pure shell-model configurations. This is in agreement with a recent calculation of the energies of the positive parity levels of ^{98}Pd by Sau *et al.*[16] They considered the coupling of four proton holes below ^{100}Sn to two neutron particles above ^{100}Sn while studying ^{98}Pd. We remark that the $6^+ \to 4^+$ transition energies which have been found for several even-A $N=84$ nuclides are larger than would have been expected (for the $\nu f_{7/2}^2$ shell-model configuration). It will be interesting to see if this empirical result for the $N=84$ system has a common basis with the $N=52$ system.

The $J^\pi=8^+$ yrast state of ^{98}Pd is relatively low lying, suggesting a $(\pi g_{9/2}^{-4})_{8^+}$ seniority-two component, while the corresponding state of ^{96}Ru occurs with a higher excitation energy. In the neighboring $N=51$ (^{95}Ru) and $N=53$ (^{97}Ru) nuclides, $J^\pi=\frac{11}{2}^-$ states have been observed[4] at about 2.4 and 1.9 MeV, respectively. Therefore, one expects the yrast $J^\pi=10^+$ states of ^{96}Ru and ^{98}Pd to have an important contribution from the $(\nu h_{11/2}^2)$ configuration. If this is the case, then the $J^\pi=8^+$ states are possibly of a different structure since the $10^+ \to 8^+$ transition energies are large. The calculations of Sau *et al.*[16] suggest that the 8^+ level of ^{98}Pd is a somewhat pure proton excitation (although they indicate that the 10^+ level should also be a proton excitation). It is interesting to note the similarity in the empirical excitation energies in the two isotones for the $J^\pi=12^+$, 14^+, and 16^+ states even though the energies of the $J^\pi=8^+$ and 10^+ states are not so similar. The relatively low excitation energy of the 12^+ states in both nuclides probably indicates the pres-

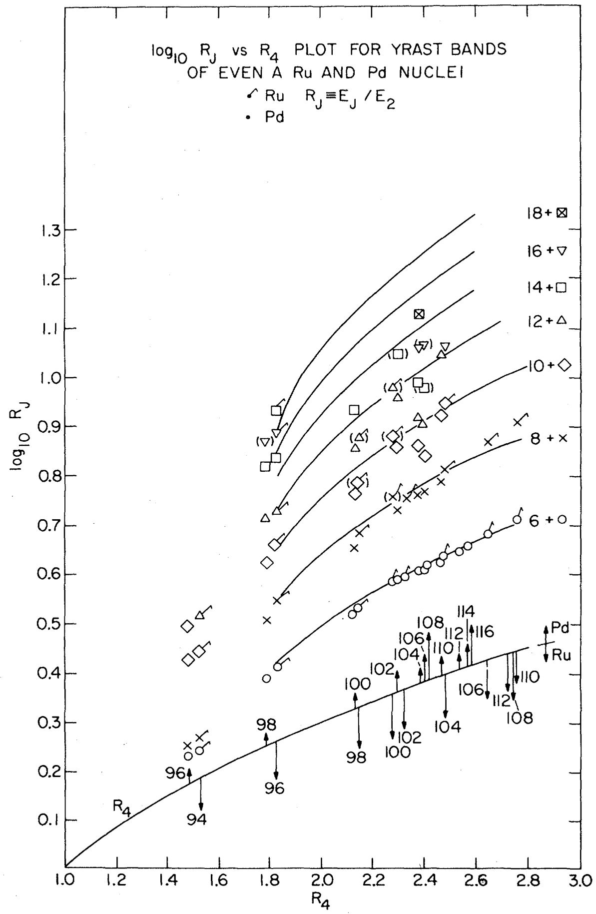

FIG. 9. A comparison of the even-A Pd ($96 \le A \le 116$) and Ru ($94 \le A \le 112$) yrast level energies to the energies predicted by the VMI model indicated by the solid curves. It is seen that the R_6 and R_8 values (where $R_J \equiv E_{J^+}/E_{2^+}$) are in excellent agreement with VMI with the exception of pseudomagic ^{100}Pd. For ^{102}Pd, the agreement continues up to the 14^+ state and for ^{100}Ru up to the 12^+ state. For ^{104,106}Pd, downward deviations occur above the 8^+ level, but in ^{110}Pd, the agreement is seen to persist to the 12^+ level.

TABLE II. Transitions in ^{96}Ru produced by 165 MeV ^{35}Cl+^{66}Zn, by 130 MeV ^{32}S+^{70}Ge, and by 71 MeV ^{12}C+^{90}Zr. The relative intensities have been corrected for the Ge(Li) detector efficiency. The A_2/A_0 and A_4/A_0 values have been slightly corrected for the finite solid angle of the detector.

	^{35}Cl+^{66}Zn			^{32}S+^{70}Ge		^{12}C+^{90}Zr		Present
E_γ	$I_\gamma^{\rm rel}$	A_2/A_0	A_4/A_0	A_2/A_0	A_4/A_0	A_2/A_0	A_4/A_0	assignment
832.51±0.09	≡100.0±0.5^{a}	+0.194±0.009	−0.079±0.015	+0.174±0.016^{a,f}	+0.003±0.024^{a,f}	+0.254±0.016	−0.069±0.024	$2^+ \rightarrow 0^+$
685.34±0.12	a,b	+0.145±0.013^{b}	−0.091±0.021^{b}	+0.191±0.021^{a}	−0.085±0.037^{a}	+0.288±0.027	−0.107±0.040	$4^+ \rightarrow 2^+$
631.64±0.10	69.4±0.5^{a}	+0.227±0.006	−0.091±0.026	+0.253±0.014^{a}	−0.058±0.020^{a}	+0.305±0.018	−0.109±0.026	$6^+ \rightarrow 4^+$
800.55±0.13	44.0±0.3	+0.303±0.013	−0.148±0.021	+0.324±0.020^{b}	−0.081±0.030^{b}	+0.433±0.022	−0.062±0.032	$8^+ \rightarrow 6^+$
866.71±0.10	40.5±0.4	+0.299±0.017	−0.140±0.027	+0.346±0.028	−0.150±0.040	+0.278±0.059	−0.194±0.086	$10^+ \rightarrow 8^+$
600.86±0.10	39.9±0.6	+0.241±0.038	−0.119±0.061	+0.115±0.029	−0.094±0.042	+0.247±0.030	−0.117±0.045	$12^+ \rightarrow 10^+$
1262.17±0.11	29.2±1.0	+0.327±0.030	−0.122±0.048	+0.218±0.040	−0.081±0.060	+0.080±0.030	−0.083±0.044	$14^+ \rightarrow 12^+$
760.68±0.17	23.6±0.7	+0.291±0.028	−0.141±0.045	+0.089±0.049^{b}	−0.091±0.072^{b}	+0.29 ±0.09	+0.02 ±0.14	$16^+ \rightarrow 14^+$
1762.8 ±0.4	4.0±2.3^{g}	+0.21 ±0.06	+0.09±0.09	+0.51 ±0.19	−0.18 ±0.26			$(18^+) \rightarrow 16^+$
741.77±0.28	13.7±1.4	−0.05 ±0.05	−0.14±0.07	−0.25 ±0.14	+0.08 ±0.21			$6^+ \rightarrow 6^+$
444.85±0.35^{g}	5.4±1.4^{g}	−0 .10±0.07	+0.03±0.12	+0.36 ±0.16	−0.19 ±0.23			$\rightarrow 10^+$
447.68±0.35^{g}	3.8±1.0^{g}	−0.20 ±0.06	+0.01±0.09	−0.12 ±0.19	−0.09 ±0.27			$\rightarrow 12^+$
1070.26±0.12	24.7±0.8	−0.16 ±0.06	−0.21±0.10	−0.07 ±0.07	−0.01 ±0.10	−0.18 ±0.05	−0.09 ±0.08	$5^- \rightarrow 4^+$
702.95±0.25^{g}	16.6±2.2^{g}	e	e	+0.037±0.031^{e}	−0.071±0.046^{e}	+0.146±0.024	−0.065±0.035	$7^- \rightarrow 5^-$
659.61±0.11	23.3±0.6	+0.13 ±0.05	−0.15±0.08	+0.330±0.026^{b}	−0.114±0.038^{b}	+0.338±0.039	−0.126±0.057	$9^- \rightarrow 7^-$
847.38±0.25^{g}	8.8±1.4^{g}	b	b	d	d	−0.23 ±0.08^{d}	−0.27 ±0.12^{d}	$9_2^- \rightarrow 9^-$
582.99±0.14	5.1±1.6^{g}	c	c	−0.21 ±0.07	+0.05 ±0.10	−0.21 ±0.11	−0.04 ±0.17	$10^- \rightarrow 9^-$
999.70±0.28	4.4±2.6^{g}	+0.16 ±0.05	+0.00±0.07	+0.11 ±0.10	+0.03 ±0.14			$(11^-) \rightarrow 10^-$
745.48±0.40^{g}	3.6±1.4^{g}	−0.051±0.036	−0.060±0.057	+0.14 ±0.05^{b}	−0.17 ±0.08^{b}			$12^- \rightarrow (11^-)$
1195.79±0.26	3.1±1.9^{g}	+0.41 ±0.08	−0.08±0.12	+0.33 ±0.12	+0.18 ±0.18			$\rightarrow 9_2^-$
952.33±0.35^{g}	5.7±1.7^{g}	+0.32 ±0.06	−0.11±0.10	+0.47 ±0.12	−0.03 ±0.17			$11_2^- \rightarrow 9_2^-$
528.27±0.30^{g}	3.2±1.7^{g}	b	b	−0.32 ±0.10^{b}	−0.06 ±0.15^{b}			$12^- \rightarrow 11_2^-$
475.52±0.35^{g}	3.6±1.0^{g}	+0.033±0.036	+0.028±0.062	−0.03 ±0.08	+0.18 ±0.12			$\rightarrow 9_2^-$

[a] Includes some intensity from the ^{96}Rh→^{96}Ru EC-β^+ decay.

[b] Unresolved from another transition.

[c] Unresolved from γ583.17 from a RdTh calibration source.

[d] Unresolved from γ846.8 in nearby ^{56}Fe.

[e] Unresolved from γ702.6 in ^{94}Mo.

[f] Unresolved from γ833.9 in ^{72}Ge (5.5% target contamination).

[g] Value obtained from ^{40}Ca+^{60}Ni, 140 MeV coincidence data.

ence of the $[(\pi g^4_{9/2})_{12^+}(p^2_{1/2})_{0^+}]_{12^+}$ configuration in ^{96}Ru and $(\pi g^{-4}_{9/2})_{12^+}$ in ^{98}Pd, i.e., 12 is the maximum spin for a positive parity level in the $Z=38-50$ shell. The yrast $J^\pi=9^-$ state of ^{96}Ru is probably related to the $(\nu g_{7/2}h_{11/2})_{9^-}$ configuration.

Transitions between collective 4p-2h states corresponding to the excitation of a pair of $g_{9/2}$ neutrons across the $N=50$ shell closure are not obviously observed in the present experiment. It is expected that a $\Delta J=2$ positive parity band could be observed built upon an excited collective $J^\pi=0^+$ state; this state is analogous to 4p-2h states deduced recently in several even Te ($Z=52$) nuclides.[4] The systematic occurrence of collective states in the $Z>50$ region corresponding to the excitation of either one or two $g_{9/2}$ protons across the $Z=50$ shell closure indicates[3,4] that the proton-excitation states are most likely to be observed when the neutron shell between $N=50$ and 82 is half-filled, i.e., for $N=66$. The Ru ($Z=44$) and Pd ($Z=46$) nuclides lie at or near the middle of the $Z=38$ to 50 proton shell. This suggests the possible observation of the collective $g_{9/2}$ neutron-excitation states. However, the situation is probably not as favorable in the Ru-Pd region, first, because there are fewer particles outside of a closed shell to encourage collective behavior. Second, in the $Z>50$ region, the excited protons in, say, a $(\pi g^2_{7/2})_{0^+}$ structure are in Nilsson orbitals that overlap significantly with occupied neutron orbitals, thus tending to lower the energy required for the structure. However, in the Ru-Pd region, the excitation of $g_{9/2}$ neutrons must be to orbitals which overlap only with unoccupied proton orbitals, thereby increasing the energy required. We note that the analogous neutron states were also not found[4] in the neighboring ^{95}Ru$_{51}$ and ^{97}Ru$_{53}$ nuclides, where they would be 3p-1h or 5p-2h states for ^{95}Ru and ^{97}Ru, respectively. However, high-spin levels of ^{94}Ru up to $J^\pi=19^+$ have recently been reported.[15,17] Some of these may be shell model states (i.e., not collective) involving the excitation of a $g_{9/2}$ neutron into a $d_{5/2}$ orbital. The agreement of the deduced levels with the shell-model calculations of Muto *et al.*,[18] who considered the neutron excitation in cooperation with the valence protons, points in this direction.

Figure 9 presents a comparison of the predictions of the variable moment of inertia (VMI) model for the even-A Pd ($96\leq A\leq 116$) and Ru ($94\leq A\leq 110$) nuclides. The solid lines refer to $\log_{10} R_J$ vs R_4, as given by the VMI equations where $R_J=E_{J^+}/E_{2^+}$. The lowest curve shows R_4 on which the abscissa values for $Z=46$ (Pd) are indicated by upward pointing arrows and $Z=44$ (Ru) by downward pointing arrows. The increase in R_4 near the middle of the neutron shell is larger for Ru with six proton holes than for Pd with four holes. While the empirical R_6 and R_8 values are in excellent agreement with the VMI predictions with the exception of pseudomagic ^{100}Pd [Ref. 2(c)] (and the R_8 values of the most deformed Ru nuclides which lie in a region of γ instability), backbending occurs in several of these nuclides above the 8^+ state. Finally, we mention that Klein[19] has also recently discussed ^{98}Pd in terms of two expressions which relate the features of both the VMI and the interacting boson approximation (IBA). However, Bonatsos and Klein find[20] that the "near magic" limits of validity are either $E_{4^+}/E_{2^+}=1.59$ or 2.0, in contrast to the VMI value of 1.82; this last value is in better agreement with the data.[2(b)(c)]

To sum up, high-spin states of ^{98}Pd have been identified and studied for the first time. The lower-spin states are in agreement with a recent study of the EC-β^+ decay of ^{98}Ag and with the results of a two-proton transfer experiment. Several new high-spin states of the isotone ^{96}Ru have been deduced from four distinct reactions. The new results should stimulate detailed calculations of the underlying nuclear structures.

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