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SPECTROSCOPY OF $^{96-98}$Ru AND NEIGHBORING NUCLEI: SHELL MODEL CALCULATIONS AND LIFETIME MEASUREMENTS * **

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High Spin states in ^{94,95}Mo, $^{94-96}$Tc, $^{96-98}$Ru and ^{97,98}Rh were populated via the ^{65}Cu(^{36}S,$xpyn$) reactions at 142 MeV. Level schemes of these nuclei have been extended up to a spin of $J \approx 20\hbar$ and an excitation energy of $E_x \approx 12-14$ MeV. Information on the high spin structure for ^{96}Tc and ^{98}Rh has been obtained for the first time. Spherical shell model calculations have been performed and compared with the experimental excitation energies. The level structures of the $N = 51$, 52 isotones exhibit single-particle nature even at the highest spins and excitation energies. A fragmentation of intensity into several branches after breaking of the $N = 50$ core has been observed. There are indications for the onset of collectivity around neutron number $N = 53$ in this mass region. A sequence of E2 transitions, reminiscent of vibrational degree of freedom, were observed in ^{98}Ru at spins just above the observed $N = 50$ core breaking. RDM lifetime measurements have been performed to ascertain the intrinsic structures of these level sequences.

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1. Introduction

While single-particle configurations dominate the level structure of nuclei with $N \leq 51$ even at high angular momenta and excitation energies ($J \approx 20\hbar$, $E_x \approx 12$ MeV) [1, 2], nuclei with $N = 54$ start exhibiting collective degrees of freedom [3]. However, not much experimental information is available on the level structures of nuclei with $51 \leq N \leq 53$. It is expected that a systematic study of the level structures of nuclei in the $N \geq 50$ and $Z \geq 40$ region, as a function of both the proton and neutron number, would lead to a better understanding of the process of generation of high angular momentum near the $N = 50$ closed shell. In particular, the following questions are of significant interest from the point of view of developing this understanding:

(1) At what neutron numbers does the transition from a spherical single-particle behavior to a collective phenomena occur?

(2) Does a half-filled proton $g_{9/2}$ orbital have a deformation stabilizing role, analogous to that observed in a half-filled neutron $g_{9/2}$ shell, in $A \approx 80$ region?

This paper presents the results of two experiments which were part of a detailed investigation of nuclei in the mass region near $A \approx 96$ that we have undertaken with the aim of exploring these questions.

2. Experimental details and results and discussion

The first experiment was performed at the 88-inch Cyclotron at the Ernest O. Lawrence Berkeley National Laboratory using a thin target to populate the high-spin states in the nuclei of interest. γ-rays were detected using the Early Implementation Gammasphere facility; details of the experiment and data analysis are provided elsewhere [5]. In the second experiment, lifetimes were measured, using the RDM technique, at ATLAS where the Argonne–Notre Dame γ-ray facility was employed in conjunction with the Notre Dame plunger. Because of the fragmentation of the total reaction strength among a number of competing reaction channels and the concomitant complexity of the observed spectra, data was collected in the coincident mode at 12 distances from 10 μm to 1000 μm, giving us an effective range of 1ps–400ps.

From the Gammasphere data, about 300 new transitions belonging to these nuclei have been placed in the respective decay schemes. The main results can be summarized as follows:

(1) The breaking of the $N = 50$ magic shell is evidenced by the observation of a number of γ rays with $E_\gamma \approx 2$ MeV at moderate spins.

(2) After the aforementioned core-breaking, the γ-ray intensity fragments into several competing cascades. This feature is similar to the level structure observed in ^{150}Dy [4], where it was attributed to the breaking of the $Z = 64$ and $N = 82$ cores. A representative scheme, for the nucleus ^{96}Ru, is shown in Fig. 1.

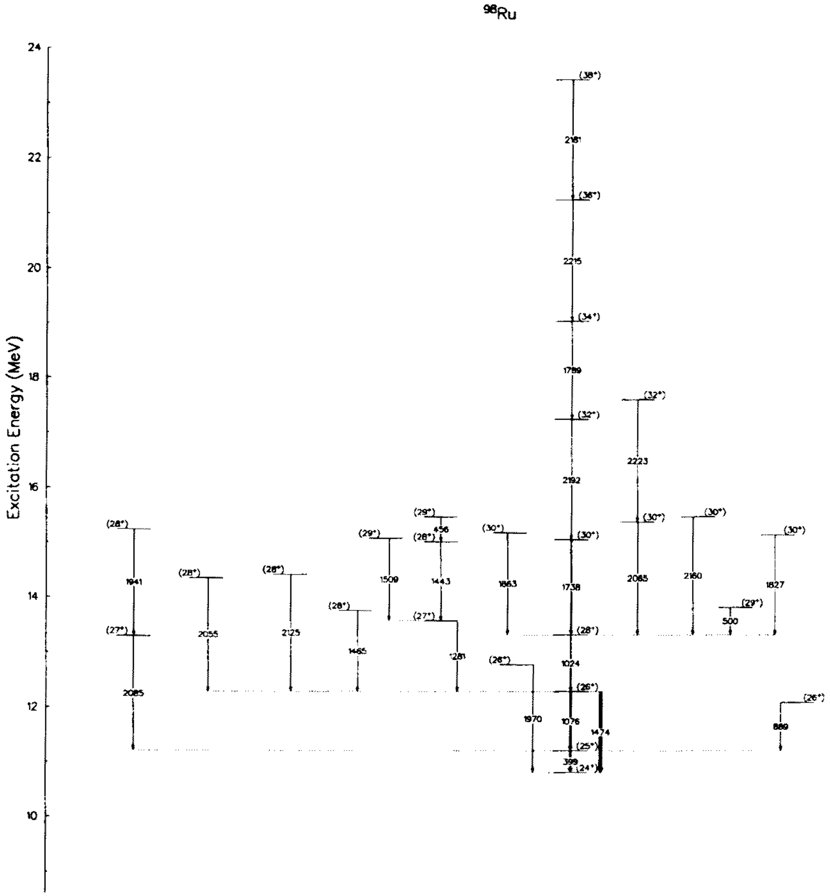

Fig. 1. Comparison of experimental excitation energies and shell model predictions for ^{96}Ru, using ^{56}Ni as the core.

(3) There are indications of the onset of collectivity around neutron number $N = 53$; see, for example, the level scheme of ^{95}Mo obtained from the present study in Ref [5].

(4) A series of consecutive E2 transitions with energies increasing with spin have been observed in $N \geq 52$ nuclei. These E2 transitions have provided tantalizing hints of the onset of collectivity as low as at $N = 52$

in this region [6]. Specifically these “band-like” structures in ^{96,97,98}Ru could be interpreted as arising from deformed configurations involving the $\nu(h_{11/2})$ quasi-neutron orbitals [6]. On the other hand, our shell model calculations (described later in the paper) also appear to reproduce these levels quite well, implying the critical importance of lifetime measurements in ascertaining the advent of collectivity in these nuclei.

(5) Several cascades of E2 transitions of approximately equal energies ($E_x \approx 2$ MeV), in one case comprising as many as five transitions, were observed immediately following the breaking of the $N = 50$ core in ^{98}Ru (Fig. 2). These cascades are reminiscent of a vibrational behavior; indeed, the main cascade would represent almost a perfect vibrator! Incidentally, a similar “quasi-vibrational” cascade had previously been observed in the nucleus ^{154}Ho and interpreted as indicative of a transition to soft triaxial shapes and increasing γ-deformations at high spins [7].

Since most of the observed level structure is of single-particle nature, the shell model is a good starting point to attempt to elucidate the underlying physics. In particular, the observation of γ-rays with $E_\gamma \sim 2$ MeV is a clear indication for the breaking of the $N = 50$ core and excitation of a $\nu(g_{9/2})$ across this shell [8]. We have carried out these calculations using the code OXBASH [9].

As a representative comparison, Fig. 3 shows the results for ^{96}Ru ($N = 52$). Clearly, the agreement between the theoretical and experimental values is quite good for the low-lying states ($J \leq 16\hbar$) in this nucleus. Of course, the low-lying states are those that are not dominated by the excitation of the $g_{9/2}$ neutron across the $N = 50$ magic shell. There is a distinct discrepancy between the calculations and the data for the higher-lying states (dominated by the $\nu((g_{9/2})^{-1})$ configurations) in case of ^{96}Ru. Indeed, similar discrepancies appear in our calculations for all nuclei with $N > 51$ and might be attributable either to the truncation of the model space or to the effective interactions used. The effect of the former could be minimized by normalizing the excitation energy of one of the high-lying states (say, the $J = 17\hbar$ level) to the experimental value. Such a normalization has been adopted, for example, by Kabadiyski *et al.* [10] for the high spins states in ^{90}Mo. As for the latter, it is hoped that this data would lead to development of effective interactions that are better suited to this region than those currently available in OXBASH.

The results obtained on lifetime measurements for $^{96-98}$Ru show values in the range of 1 to 35 ps; the results for ^{96}Ru are represented in Table I. The B(E2)’s extracted from these lifetimes are in qualitative agreement with the shell model calculations and experimental B(E2) values lie within the range of single-particle estimates. Thus, the observed E2 transitions in $^{96-98}$Ru exhibit primarily single-particle nature.

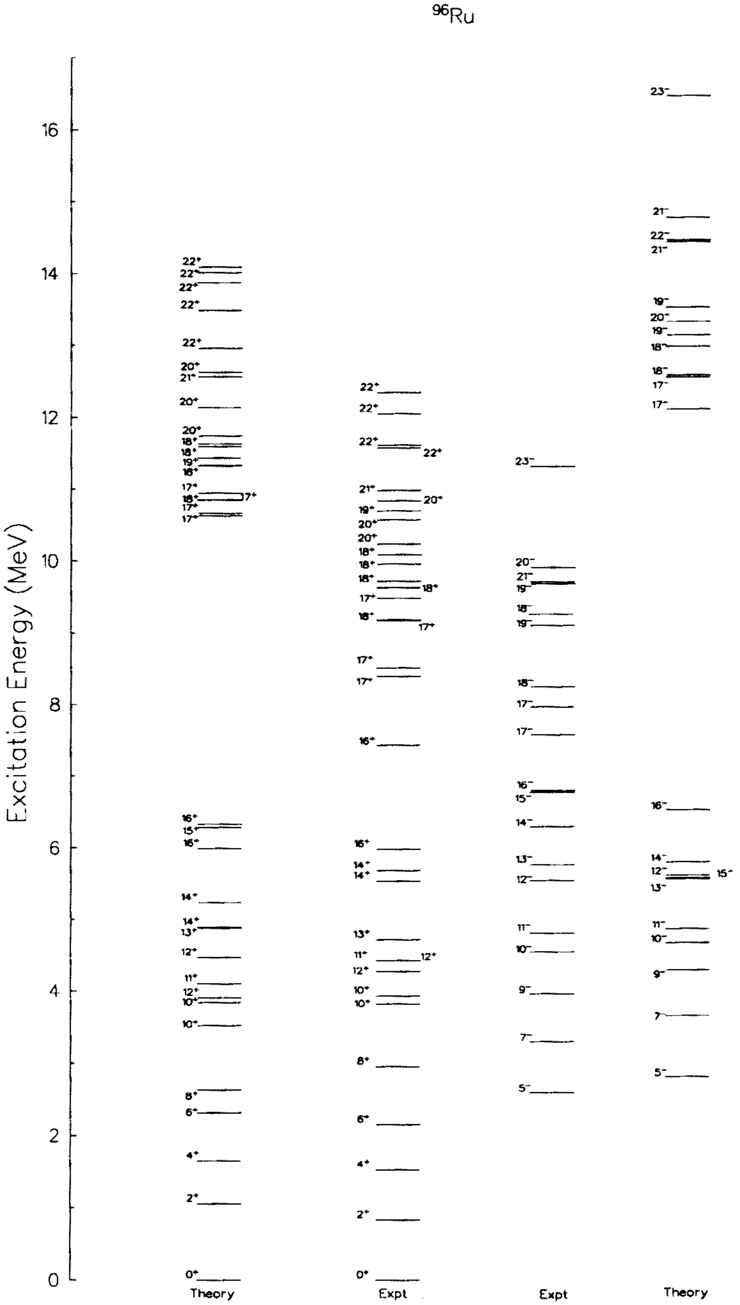

Fig. 2. Level scheme for ^{96}Ru from the present work.

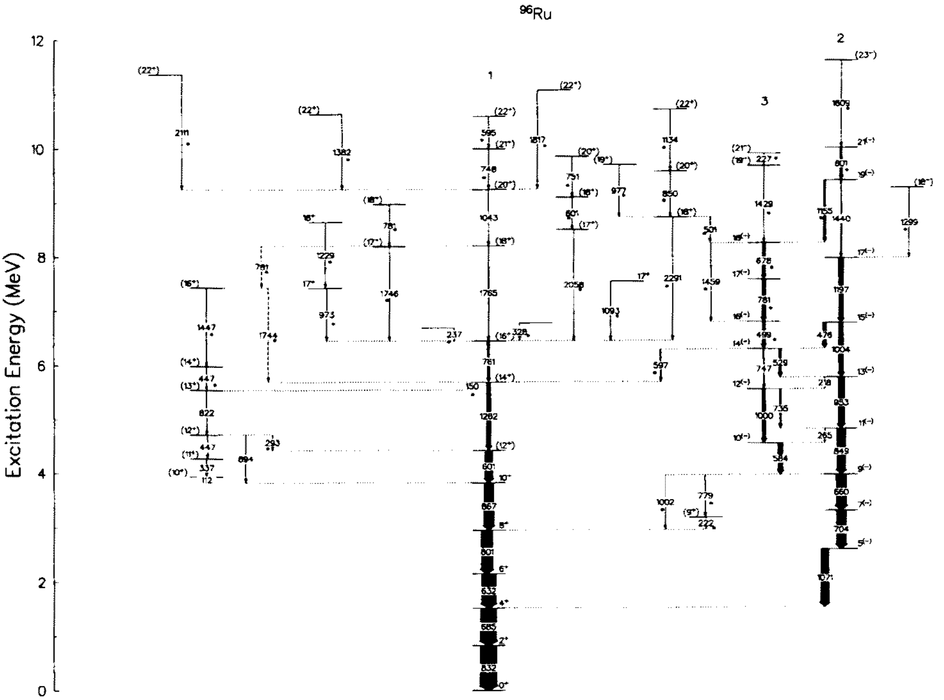

Fig. 3. Partial level scheme of ^{98}Ru, highlighting the E2 sequences observed up to (38^+) and reminiscent of a vibrational degree of freedom.

TABLE I

Spins, lifetimes, and comparison between the experimental and theoretic B(E2) values for levels up to $J = 14^+(17^-)$ in ^{96}Ru.

$J_i \to J_f$	τ(ps)	B(E2)$_{\mathrm{expt}}$ $10^{-3}e^2b^2$	B(E2)$_{\mathrm{SM}}$ $10^{-3}e^2b^2$	B(E2)$_{\mathrm{expt}}$ (wu)	B(E2)$_{\mathrm{SM}}$ (wu)
1	2	3	4	5	6
$2^+ \to 0^+$	5.10 (1.2)	40.1	41.46	15.30	15.8
$4^+ \to 2^+$	20.3 (1.3)	26.4	52.72	10.1	20.1
$6^+ \to 4^+$	30.3 (1.4)	26.7	39.38	10.2	15.0
$8^+ \to 6^+$	14.2 (0.2)	17.37	20.72	6.63	7.91
$10^+ \to 8^+$	5.10 (0.5)	32.64	39.5	12.5	15.1
$12^+ \to 10^+$	30.9 (4.8)	33.66	34.44	12.8	13.2

1	2	3	4	5	6
$14^+ \rightarrow 12^+$	26.0 (3.4)	1.20	31.53	0.46	12.0
$7^- \rightarrow 5^-$	12.2 (0.4)	38.3	49.41	14.6	18.9
$9^- \rightarrow 7^-$	16.0 (0.4)	40.7	62.12	15.5	23.7
$11^- \rightarrow 9^-$	4.30 (0.1)	43.0	53.1	16.4	20.3
$13^- \rightarrow 11^-$	25.1 (2.9)	4.13	45.15	1.57	17.2
$15^- \rightarrow 13^-$			35.05		13.38
$17^- \rightarrow 15^-$	$\leq$ 5.0 (0.2)	$\geq$ 6.63	$\geq$ 24.58	$\geq$ 2.53	$\geq$ 9.36

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