CONF-951274--3
ANL/PHY/CP-- 89517

SHELL MODEL AT GAMMASPHERE: STUDIES IN THE $A \approx 96$ REGION

U. Garg, S.S. Ghugre, B. Kharraja, G. Smith
Department of Physics, University of Notre Dame, Notre Dame, IN 46556.

I. Ahmad, M.P. Carpenter, B. Crowell, R.V.F. Janssens, T.L. Khoo, T. Lauritsen, D. Nisius
Physics Division, Argonne National Laboratory, Argonne, IL 60439.

W.F. Mueller, W. Reviol, L.L. Riedinger
Department of Physics, University of Tennesse, Knoxwille, TN 37996.

R. Kaczarowski
Soltan Institure of Nuclear Studies, 05-400 Swierk, Poland.

High-spin states in ^{94,95}Mo, ^{94,95,96}Tc, ^{96,97,98}Ru and ^{97,98}Rh were populated via the ^{65}Cu(^{36}S, xpyn) reactions at 142 MeV. We have observed about 300 new transitions belonging to these nuclei, and their level schemes 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 high spins and excitation energies ($J \approx 20\hbar, E_x \approx 12-14$ MeV). *A fragmentation of intensity into several branches after* the 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, indicating an onset of the vibrational degree of freedom, was observed in ^{98}Ru at spins just above the observed $N = 50$ core breaking.

1 Introduction

While single particle configurations dominate the level structure of nuclei with $N \leq 51$ even at high angular momenta ($J \approx 20\hbar, E_x \approx 12$ MeV),[1,2] nuclei with $N \geq 54$ begin exhibiting collective degrees of freedom.[3,4] 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 number does collective motion become competitive with single-particle behavior?

(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 the $A \approx 80$ region?

This paper presents preliminary results of a detailed investigation of nuclei in the mass region near $A \approx 96$ that we have undertaken at GAMMASPHERE with the aim of exploring these questions.

2 Experimental Details

The experiment was performed at the 88-inch Cyclotron at the Ernest O. Lawrence Berkeley National Laboratory. The ^{65}Cu(^{36}S, xpyn) reaction at E(^{36}S) =142 MeV, with two self-supporting (0.5 mg/cm^2) targets, was used to populate the high-spin states in the nuclei of interest. Gamma rays were detected using the Early Implementation GAMMASPHERE facility. Approximately 400 million events (with $fold \geq 3$) were recorded; the data consisted of approximately 73% triples, 19% quadrupoles and 4% quintuples.

The data were sorted into 2 symmetrized 3-dimensional histograms (cubes), in the Radford [5] and Kuehner [6] formats. The Radford format cube was analyzed using the RADWARE analysis package,[7] which used the generalized background subtraction [8] for extracting double gates from the cube. Double gated spectra were extracted from the Kuehner format cube, using the FUL background subtraction algorithm.[9] Multipolarity assignments were made according to the procedure described by Bernstein *et al.* [10] The strongest reaction channels in this experiment were those populating the ^{96,97,98}Ru nuclei. However, data with sufficient statistics were available on some of the weakly populated channels, such as that leading to ^{98}Rh, to yield interesting new information on the level structure of these nuclei as well.

3 Results

In all, about 300 new transitions belonging to various isotopes of Mo, Tc, Ru and Rh have been placed in the respective decay schemes. The level schemes of these nuclei have been substantially extended (up to $J \approx 20\hbar$ and $E_x \approx 12$ MeV). The main features 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 in these nuclei.[11]

(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, where it was attributed to the breaking of the Z = 64 and $N = 82$ cores.[12] A representative scheme, for the nucleus ^{96}Ru, is shown in Fig. 1.

(3) There are indications of the onset of collectivity around neutron number $N = 53$. For example, Fig. 2 shows the level scheme for ^{95}Mo obtained from the present study. Of particular interest is the rotational-band-like structure built on a $(15/2)^-$ state; the observed level spacings correspond to a nearly constant dynamic moment of inertia with indications of, possibly, a "band crossing" at the highest spins.

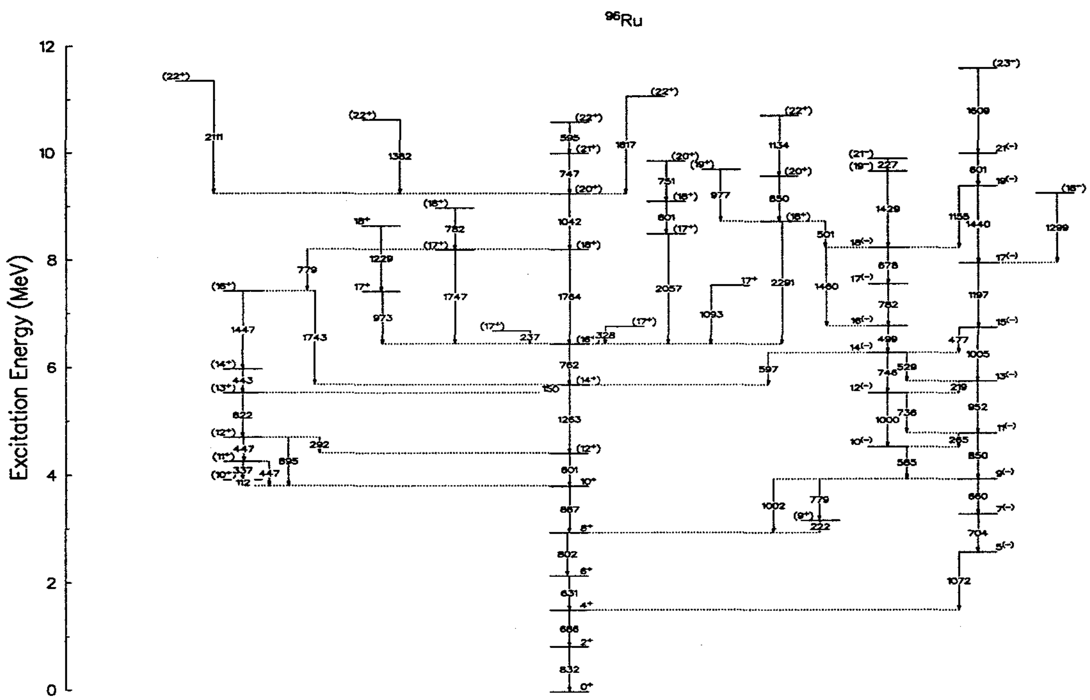

Fig. 1. Level scheme for ^{96}Ru from the present work. The low-lying levels were known from Lederer *et al.* [13]

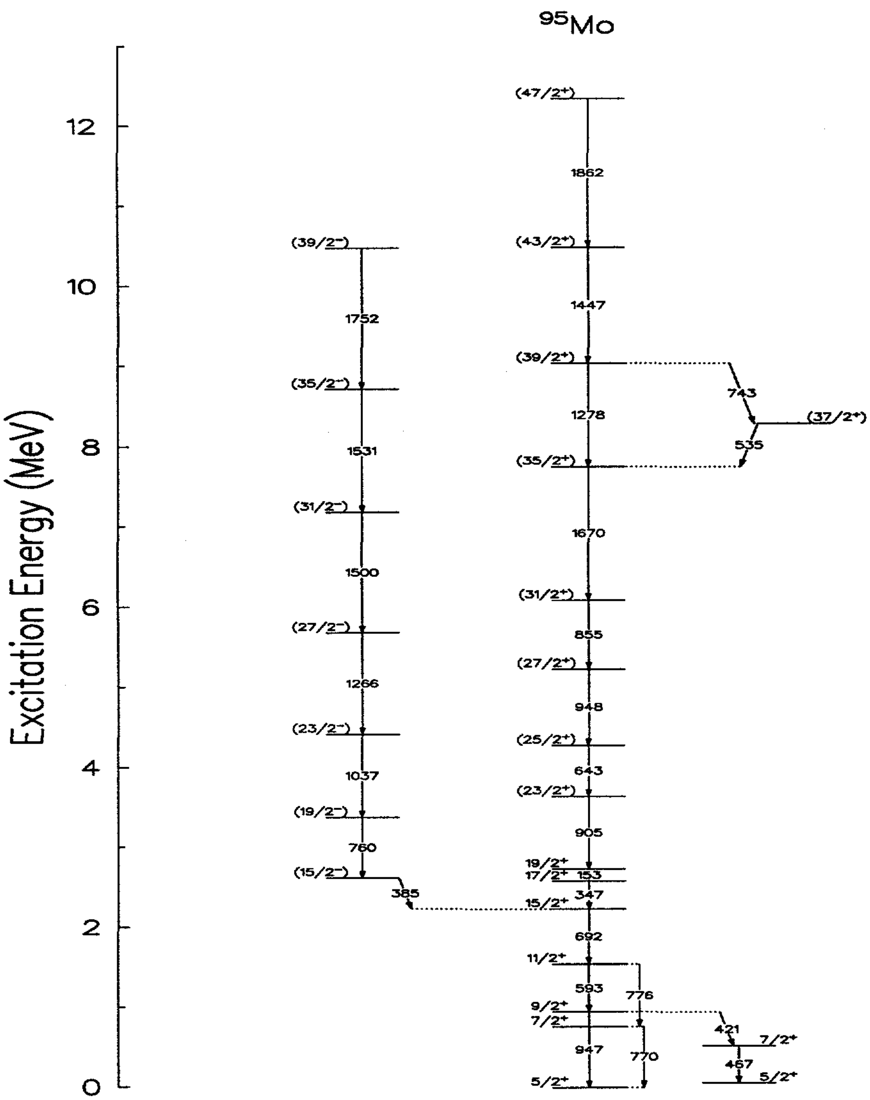

Fig. 2. Level scheme for ^{95}Mo obtained from the present work. The low-lying states were known from Lederer *et al.* [14] The E2 sequence built on the $(15/2)^-$ state is suggestive of the onset of collective motion.

(4) A series of consecutive E2 transitions with energies increasing with spin has been observed in the negative parity branches of the level schemes of the $N \geq 52$ nuclei. These E2 transitions have provided tantalizing hints of the onset of collectivity as low as at $N = 52$ in this region.[15] 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. [15] 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. 3).

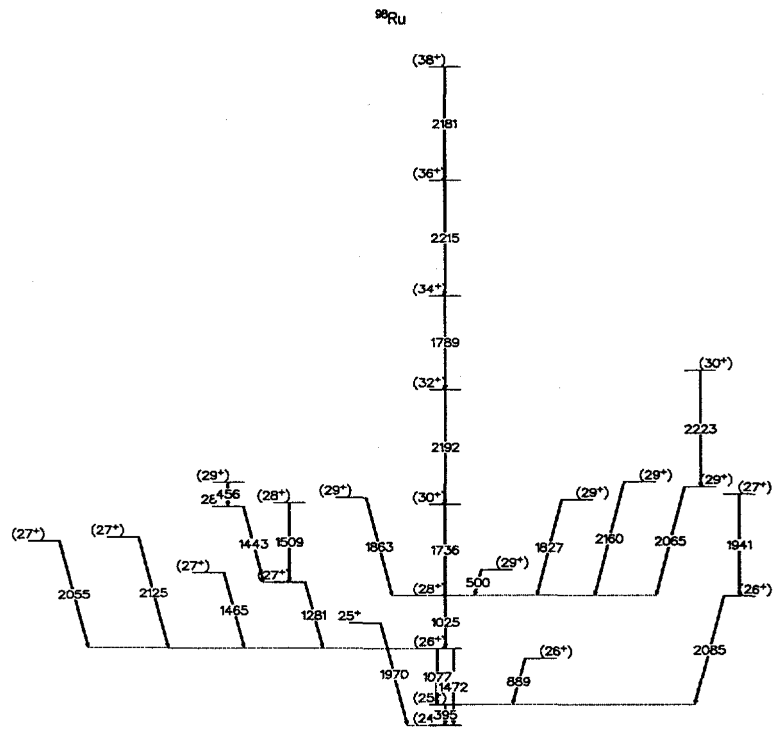

Fig. 3. Partial level scheme of ^{98}Ru, highlighting the E2 sequences observed up to (38^+) and reminiscent of vibrational bands (see text).

These cascades are reminiscent of a vibrational behavior. 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.[16]

(6) Information on the high spin level structure for ^{96}Tc and ^{98}Rh was obtained for the first time in the present work; the level scheme for ^{98}Rh is shown in Fig. 4.

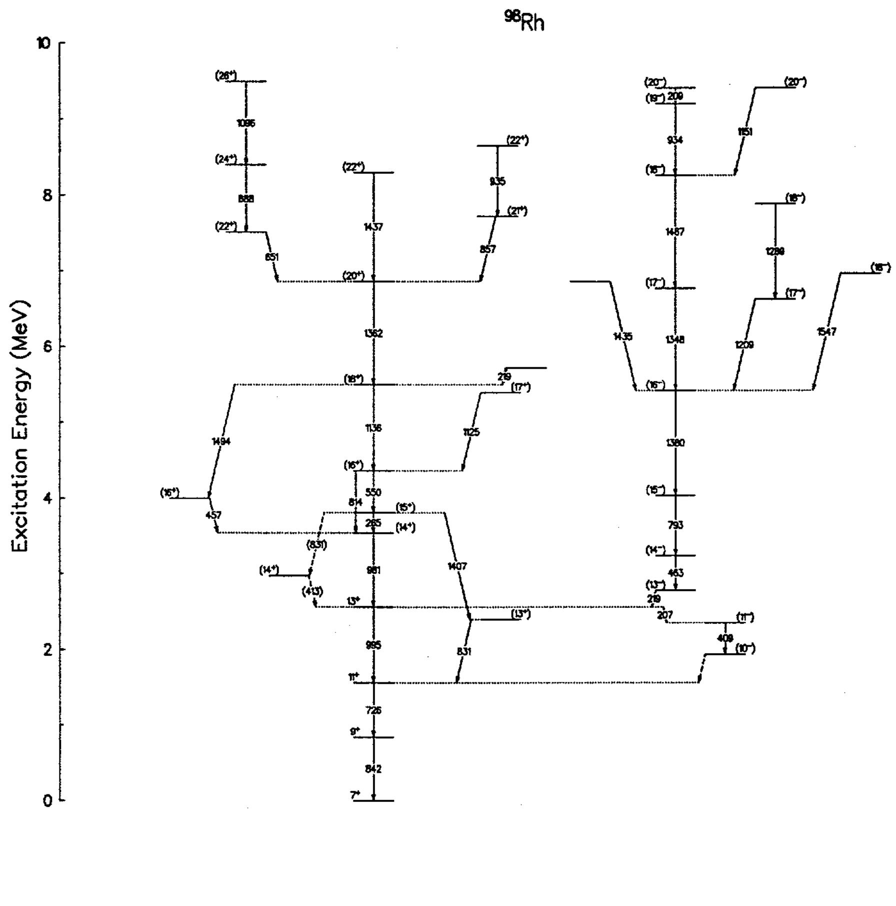

Fig. 4. Level scheme for ^{98}Rh, as obtained from this work. The low-lying states were known from Behar *et al.* [17]

4 Discussion

Since most of the observed level structure is of single-particle character, the shell model is a good starting point to attempt to elucidate the underlying physics. In particular, the observation of a γ ray with $E_\gamma \approx 2$MeV is a clear indication for the breaking of the $N = 50$ core and excitation of a $\nu(g_{9/2})$ across this shell.[11] We have carried out shell-model calculations using the code OXBASH.[18] In our earlier study of the high spin states in ^{94}Tc, we had reported on the comparison of the experimentally observed energy levels with the shell-model calculations using ^{88}Sr, ^{66}Ni and ^{56}Ni as the core, respectively;[2] details regarding the valence orbitals and the effective interactions used are provided therein. The low-lying levels (up to $J = 14^+, 15^-$) were well reproduced using these model spaces and, as expected, the inclusion of the $\nu(f_{5/2}, p_{3/2})$ orbitals (*i.e.* using the ^{56}Ni core) resulted in somewhat better agreement with the experimental level energies. The discrepancies for the high-lying levels ($J \geq 16^-$) could be attributed to either the effective interactions used or the truncation of the model space. The level scheme of ^{94}Tc has been substantially extended in the present work. Also, the earlier calculations did not incorporate the $\nu(h_{11/2})$ orbital which is likely to play a dominant role in this mass region, as pointed out by Reviol *et al.*[15] The extensive new information available on the level structure of ^{94}Tc, coupled with the availability of a model space incorporating the $\nu(h_{11/2})$ orbital along with the ^{56}Ni core, prompted us to reinvestigate the level sequence of ^{94}Tc. The "new" model space comprised of ^{56}Ni as the core and $\pi(f_{5/2}, p_{3/2}, p_{1/2}, g_{9/2})$ and $\nu(f_{5/2}, p_{3/2}, p_{1/2}, g_{9/2}, g_{7/2}, d_{5/2}, d_{3/2}, s_{1/2}, h_{11/2})$ as the valence proton and neutron orbitals, respectively. A combination of schematic and experimental two-body matrix elements, provided for in OXBASH, was used. The model space was internally truncated by taking into account only the most dominant configurations for a given angular momentum state; details of the truncation procedure are provided elsewhere.[11] For levels with $J \approx 15\hbar$, no neutron excitations across the $N = 50$ core were allowed, while the $\pi(f_{5/2}, p_{3/2})$ orbitals were completely occupied (*i.e.* proton excitations were allowed only within the $p_{1/2}, g_{9/2}$ orbitals). A single $g_{9/2}$ neutron excitation was permitted across the $N = 50$ magic shell (and into the next major oscillator shell) for the higher angular momentum states.

As representative comparisons, Figs. 5 and 6 show the results for ^{94}Tc ($N = 51$) and ^{96}Ru ($N = 52$), respectively. Clearly, the agreement between the theoretical and experimental values is quite good for the low-lying states ($J \leq 16\hbar$) in both nuclei and also for the higher-spin states in ^{94}Tc. Of course, the low-lying states are those that do not involve 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 scheme 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.*[19] 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 of nuclei than those currently available in OXBASH.

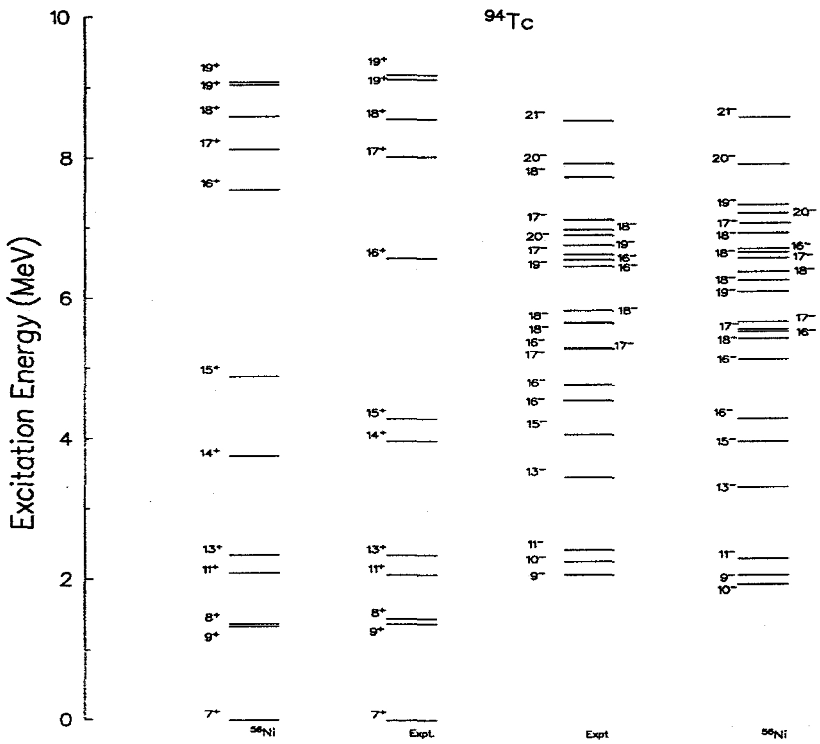

Fig. 5. Comparison of experimental excitation energies in ^{94}Tc and shell model predictions for those levels, using ^{56}Ni as the core.

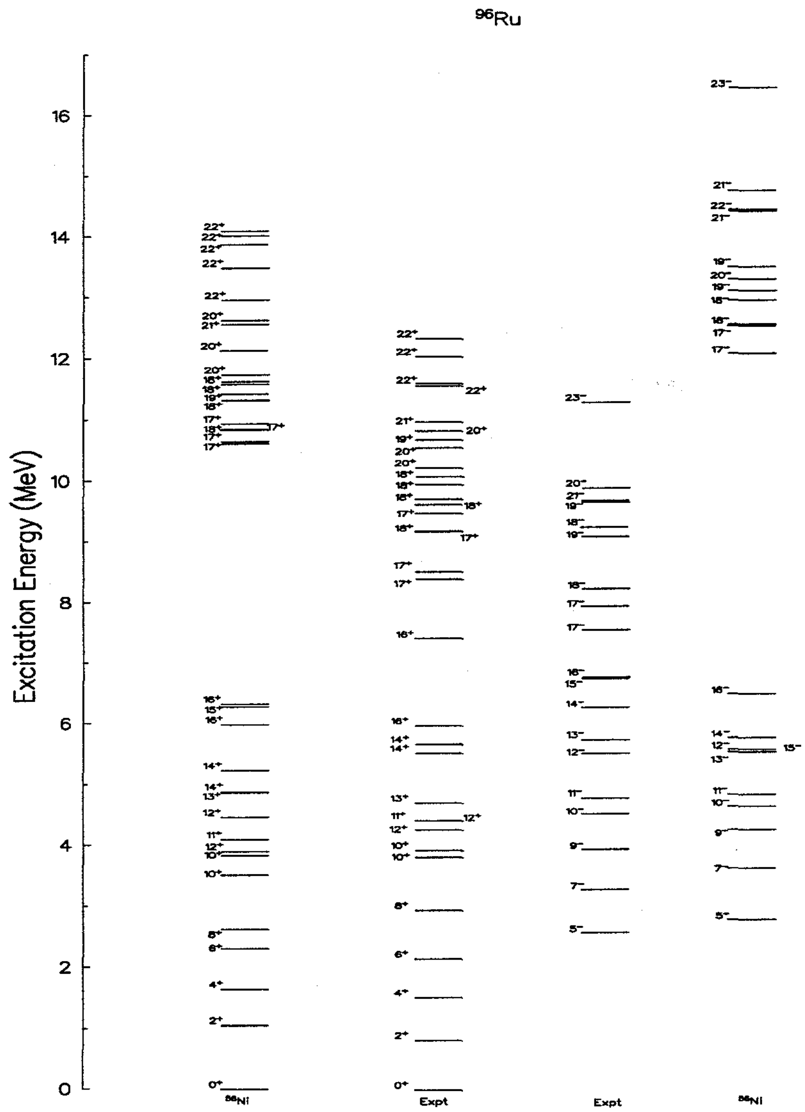

Fig. 6. Comparison of experimental excitation energies in ^{96}Ru and shell model predictions for those levels, using ^{56}Ni as the core.

It has been noted in earlier studies that in the $N \approx 52$ nuclei, the shell model and the collective model give similar results for the low-lying states.[20] In particular, for the low-lying even-parity states in ^{95}Tc, the shell model calculations gave results very similar to those with the particle+vibrating core model with respect to the transition rates.[20] As mentioned earlier, the "band-like" E2 cascades observed in $^{96-98}$Ru nuclei are, likewise, reasonably well reproduced in our shell model calculations, even with a limited model space. For example, Fig. 7 illustrates the comparison between the experimental levels comprising this cascade in ^{96}Ru and the shell-model calculations for these levels, using the small configuration space (*i.e.* with the ^{88}Sr core). It is clear that any determination of the suggested collective nature of these cascades must await appropriate lifetime measurements.

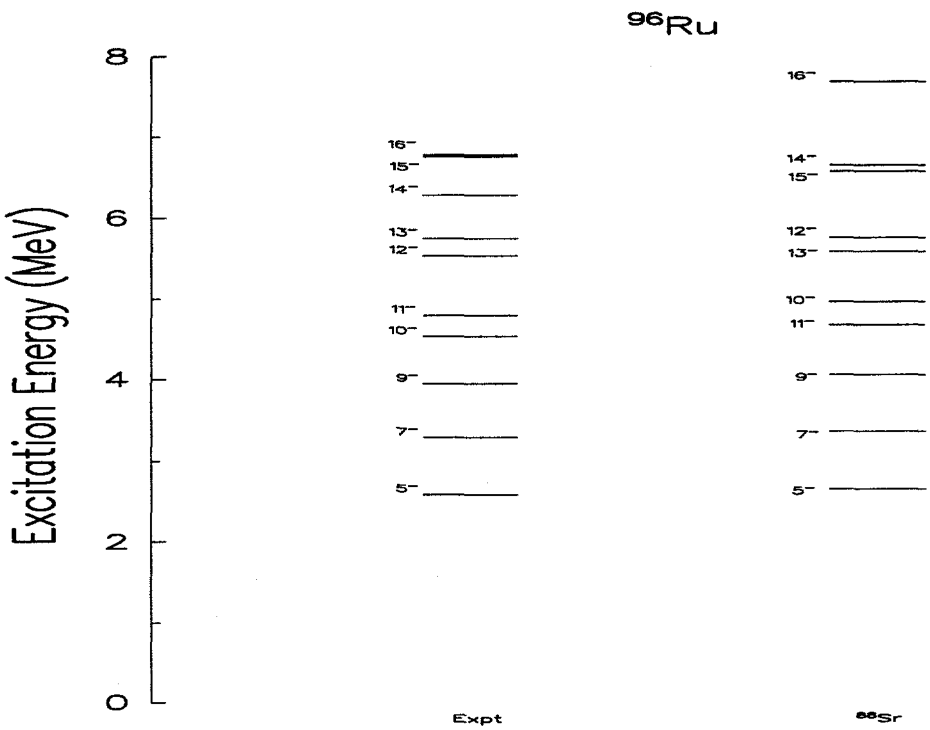

Fig. 7. Comparison of shell-model predictions and the excitation energies of levels in the "band-like" E2 cascade observed in ^{96}Ru.

5 Summary and Conclusions

Extensive level schemes of the nuclei ^{94,95}Mo, ^{94,95,96}Tc, ^{96,97,98}Ru, and ^{97,98}Rh have been established from a data set obtained with the Early Implementation GAMMASPHERE. For ^{96}Tc and ^{98}Rh, information on the high-spin structure has been obtained for the first time. The level structures of the N$= 51, 52$ isotones exhibit single-particle nature up to high spins and excitation energies ($J \approx 20\hbar, E_x \approx 12 - 14$ MeV). A fragmentation of intensity into several branches after the breaking of the N $= 50$ core is observed. The core-breaking picture is supported by the shell-model calculations presented in this paper. The discrepancies remaining between the results of the shell-model calculations and the experimentally observed high-spin energy levels in the N ≥ 52 nuclei point to the need for the development of suitable effective interactions for this region of nuclei.

Special attention has been focussed on possible evidence for the onset of collectivity beyond the N $= 50$ shell. The high-spin part of positive-parity states in ^{98}Ru, just above the core-breaking, seems to indicate an onset of the vibrational degree of freedom. There are indications also of the onset of rotational motion in some of these nuclei around N $= 53$ at lower-spin states, presumed to be of negative parity. However, our shell-model calculations also appear to describe these levels quite well. This stresses the critical importance of lifetime measurements as a necessary complement to the energy-level information in ascertaining the advent of collectivity in these nuclei.

Acknowledgments

Invaluable assistance from the GAMMASPHERE staff is gratefully acknowledged. This work has been supported in part by the National Science Foundation (grant number PHY94-02761), the Department of Energy (contract numbers W-31-109-ENG-38 and DE-FG05-87ER40361) and the U.S.-Poland Maria Sklodowska-Curie Joint Fund II (project number PPA/DOE-93-153).

References

1. S.S. Ghugre *et al.*, *Phys. Rev.* C **40**, 1346 (1994).
2. S.S. Ghugre *et al.*, *Phys. Rev.* C **51**, 2809 (1995).
3. V. Ravikumar *et al.*, *J. Phys. G. Nucl. Part. Phys* **20**, 441 (1994).
4. M.J.A. de Voigt *et al.*, *Nucl. Phys.* A **270**, 141 (1976).
5. D.C. Radford *et al.*, *Nucl. Instrum. Methods* A **258**, 111 (1987).

6. J.A. Kuehner *et al.* in *Proc. of the International Conference on Nuclear Structure at High Angular Momentum, Ottawa, May 1992*, AECL-10613, pp. 43.
7. D.C. Radford, *Nucl. Instrum. Methods* A **361**, 297 (1995).
8. G. Palmeta *et al. Nucl. Instrum. Methods* A **234**, 476 (1985).
9. B. Crowell *et al. Nucl. Instrum. Methods* A **355**, 575 (1995).
10. L.A. Bernstein *et al. Phys. Rev.* C **52**, R1171 (1995).
11. S.S. Ghugre *et al. Phys. Rev.* C **52**, 1811 (1995).
12. M.A. Deleplanque *et al.*, *Phys. Lett.* B **195**, 17 (1987).
13. C.M. Lederer *el al.*, *Nucl. Phys.* A **169**, 449 (1971).
14. C.M. Lederer *el al.*, *Nucl. Phys.* A **169**, 489 (1971).
15. W. Reviol *et al.*, *Nucl. Phys.* A **557**, 391c (1993).
16. C. Baktash in *High Angular Momentum properties of Nuclei*, N.R. Johnson, Editor (Harwood Academic, New York, 1983) pp. 207.
17. M. Behar *et al.*, *Z. Phys.* A **314**, 111 (1983).
18. B.A. Brown *et al.*, MSU-NSCL report number 524, (1984), unpublished.
19. M.K. Kabadiyski *et al.*, *Z. Phys.* A **343**, 165 (1992).
20. L.D. Skouras *et al.*, *Phys. Rev.* C **15**, 1873 (1977).