Odd-Parity Rotational-Band Structure in ^{48}V

L. E. Samuelson, W. H. Kelly, F. M. Bernthal, R. A. Warner, and Wm. C. McHarris

Recently, rotational-like band structure has been reported in odd-A ^{49}Cr by R. W. Zürmuhle, et al.[1] and in odd-A ^{49}V by S. L. Tabor and R. W. Zürmuhle.[2] The existence of such band structure suggests that nuclei in the middle of the $f_{7/2}$ shell are deformed. The odd-odd ^{48}V nucleus might therefore be expected to be deformed and possess rotational-like bands. In fact, a band based upon a 518-keV, $K^{\pi}=1^{(-)}$ state in ^{48}V has been reported by B. Haas and P. Taras.[3] As a supplement to our previous studies of low-spin ^{48}V states using the $^{48}Ti(p,n\gamma)$ reaction,[4] we have used the $^{46}Ti(\alpha,pn\gamma)$ reaction to study high-spin ^{48}V states. In a preiminary paper[5] we reported, in addition to the above mentioned $1^{(-)}$ band, the existence of a band built upon a 1099-keV, $K^{\pi}=4^{(-)}$ state.

Two experiments were performed using the $^{46}Ti(\alpha,pn\gamma)$ reaction. In the first, γ-γ coincidences were measured using a high resolution Ge(Li)-Ge(Li) spectrometer. A 1 mg/cm^2, 86.1% isotopically enriched ^{46}Ti target was bombarded with 30-MeV alpha particles from the MSU Cyclotron. Coincidence events were stored on magnetic tape and later sorted off-line using background subtraction. New ^{48}V γ rays were identified by their appearance in gates of previously well-known γ rays from our $(p,n\gamma)$ work. In the second experiment γ-ray excitation functions were measured with bombarding alpha-particles having energies of 24-42 MeV in 3-MeV steps. These data yielded γ-intensity information as well as nuclidic assignment and qualitative suggestions for spin assignments of high-spin states. The odd parity level scheme of ^{48}V organized to exemplify the band structure is shown in Fig. 1. The spin and parity assignments shown are based upon our previous $(p,n\gamma)$[4] and present works.

As the ^{48}V nucleus is allowed a prolate deformation, the $d_{3/2}$ [202↓], $\Omega^{\pi}=3/2^+$ single-particle orbit approaches the $f_{7/2}$ [321↑], $\Omega^{\pi}=3/2^-$ orbit. If the odd proton is allowed to occupy this orbit (with little expense in energy) and the odd neutron remains in its ground-state orbit, $f_{7/2}$[312↑], $\Omega^{\pi}=5/2^-$, a low-lying $K^{\pi}=1^-$, $\Sigma=1$ state results. The 518-keV, $1^{(-)}$ state can be identified as this state. A $K^{\pi}=4^{(-)}$ state at 1099 keV can be identified as the $\Sigma=0$ coupling of this same configuration. As can be seen in Fig. 1, both intrinsic states exhibit well defined band structures built upon them. The $4^{(-)}$ band is reasonably normal following the I(I+1) rule with an average rotational constant of 53 keV. The $1^{(-)}$ band however is strongly perturbed with a very large odd-even shift. The rotational constant for this band derived from the energy spacings of the odd- and even-spin members is 56 keV, very close to the value derived for the $4^{(-)}$ band. This odd-even shift within the $1^{(-)}$ band may be caused by the residual proton-neutron interaction which has (to zeroth order) caused an odd-even shift in a 0^- band formed by the odd proton being in the $d_{3/2}$ [202↓], $\Omega^{\pi}=3/2^+$ orbit and the odd neutron in the $f_{7/2}$ [321↑], $\Omega^{\pi}=3/2^-$ orbit. This odd-even shift is then felt in the $1^{(-)}$ band to first order by the Coriolis interaction. A quantitative treatment of the proton-neutron interaction here is difficult because the perturbing $0^{(-)}$ band has not yet been identified.

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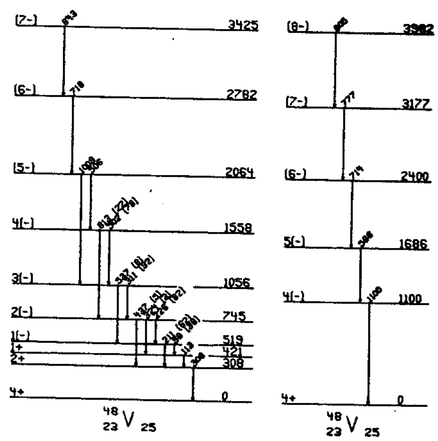

Figure 1--^{48}V odd-parity level scheme exemplifying rotational-like band structure. Note that the energy scales of the two bands are not equal.

In-Beam Gamma Ray Investigations of Medium Mass Odd-Odd Nuclei

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Knowledge of the residual p-n interaction is essential for a full understanding of the structures of nuclei. Odd-odd nuclei give the nuclear spectroscopist a convenient handle for examining that interaction. These nuclei have been studied very little, and then mainly in the low Z nuclei. This situation is understandable when one views the complexities of spectra from reactions involving medium and heavy mass nuclei. States are present at relatively low energies in odd-odd nuclei whose nature would force them to relatively high and more inaccessible energies in other nuclei, e.g. even-even.

It has been only in the last few years, with the development of high resolution gamma-ray spectroscopy and computer techniques for the analysis and manipulation of large amounts of data, that it has been possible to study these nuclei with any degree of confidence. At the same time, the availability of large computers have made related theoretical studies feasible.

Because of the complexity of odd-odd nuclei and the limitations of a given experiment, it is highly desirable to use more than one tool to study the states. We have embarked on a series of studies using in-beam gamma-ray spectroscopy via the (p,nγ), (p,xnγ), (α,xnγ) reactions and supplementing these with data from direct reactions, e.g. (p,d), (^{3}He,t) and (α,t) on representative nuclei throughout the periodic table, including examples of both spherical and deformed nuclei.

The nuclei that have been under study using these techniques are $^{56}_{27}Co_{29}$, $^{48}_{23}V_{25}$, $^{104}_{47}Ag_{57}$, $^{116}_{51}Sb_{65}$, $^{118}_{51}Sb_{67}$, $^{140}_{59}Pr_{81}$, and $^{182}_{75}Re_{107}$. The investigations of ^{56}Co are complete and have been published.[1] The study of ^{48}V is nearing completion and those very interesting results are summarized in another section of this report. The recent results obtained on the other nuclei are briefly given below. Earlier annual reports contain additional information.

Levels of ^{104}Ag from ^{104}Pd(p,nγ) and ^{103}Rh(α,3nγ)

The levels of odd-odd ^{104}Ag have been studied by observing γ rays following the ^{104}Pd(p,nγ) and ^{103}Rh(α,3nγ) reactions. From the ^{104}Pd(p,nγ) reaction the measurement of γ-γ coincidences with E_p = 6.04 MeV (from the MSU Cyclotron) and γ-ray excitation functions with E_p = 5.051 to 6.004 MeV in ≃50-keV steps (from the Western Michigan University Tandem Van de Graaff) have resulted in the ^{104}Ag decay scheme shown in Fig. 1. The labelled spins and parities of the ground and isomeric states are from atomic-beam measurements[2] while those labelling remaining selected states are from the β decay of the 0^+ ground state of ^{104}Cd as measured by Münnich, et al.[3] Since primarily low-spin states (i.e. J<6) are expected to be excited most strongly with the (p,nγ) reaction at the beam energies used, experiments using the ^{103}Rh(α,3nγ) reaction were performed to look for high-spin states in ^{104}Ag. γ-γ coincidences with E_α=38 MeV and γ-ray excitation functions with E_α=31-46 MeV in 3-MeV steps (all α's from the MSU cyclotron) have been measured. The analyses of these data are still in progress.

Several important features of ^{104}Ag have been learned. First, the 2^+ isomeric level energy previously known to be less than 10 keV has been determined indirectly to be 6.88±0.05 keV. (See Fig. 1) Second, the 123.78-keV γ ray decays to the 2^+ isomeric level. Münnich, et al.,[3] could not uniquely determine the order of the 26.71- and 123.78-keV γ rays. Third, the (p,n) Q-value is -5.053±0.025 MeV for the ground state. This is somewhat higher than -4.882±0.030 MeV estimated from atomic mass differences by Wapstra and Gove.[4] Finally, the (α,3nγ) and (p,nγ) spectra look quite different. Many γ rays, apparently from high-spin states, appear in the (α,3nγ) spectra but are completely absent in the (p,nγ) spectra. Similarly, many γ rays from low-lying low-spin states are absent in the (α,3nγ) spectra.

We plan to compare the γ-excitation functions (in the form of cross-section ratios) from the (p,nγ) reaction with predictions of statistical compound nuclear model (using the code MANDY[5]) to make spin assignments to the levels of ^{104}Ag below 800 keV of excitation. Also, the γ-excitation functions from the (α,3nγ) reaction should yield estimates of spin assignments to those high-spin states that will be determined from γ-γ coincidence data.

The Low Energy States of $^{116}_{51}Sb_{65}$

We have continued the series of in-beam gamma-ray experiments using the (p,nγ) reaction on ^{116}Sn. These consist of excitation functions, gamma-gamma coincidences, gamma-ray angular distributions and lifetime measurements. In addition, some preliminary work has been done using the (α,3nγ) reaction which transfers larger amounts of angular momentum. These data are still undergoing analysis.

The target used was a 1 mg/cm^2 foil of ^{116}Sn enriched to approximately 95%. Excitation

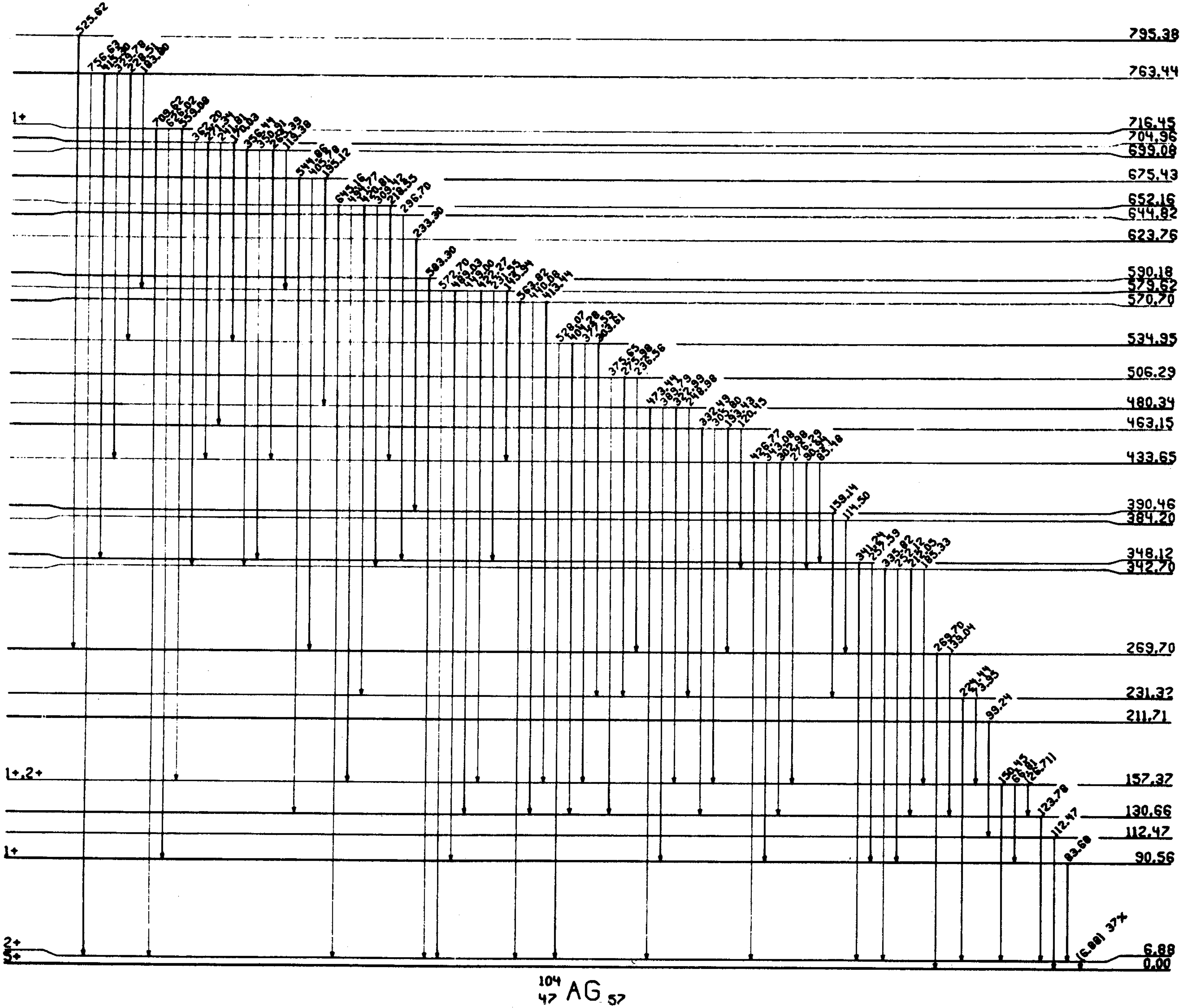

Fig. 1.--Tentative level scheme for ^{104}Ag.

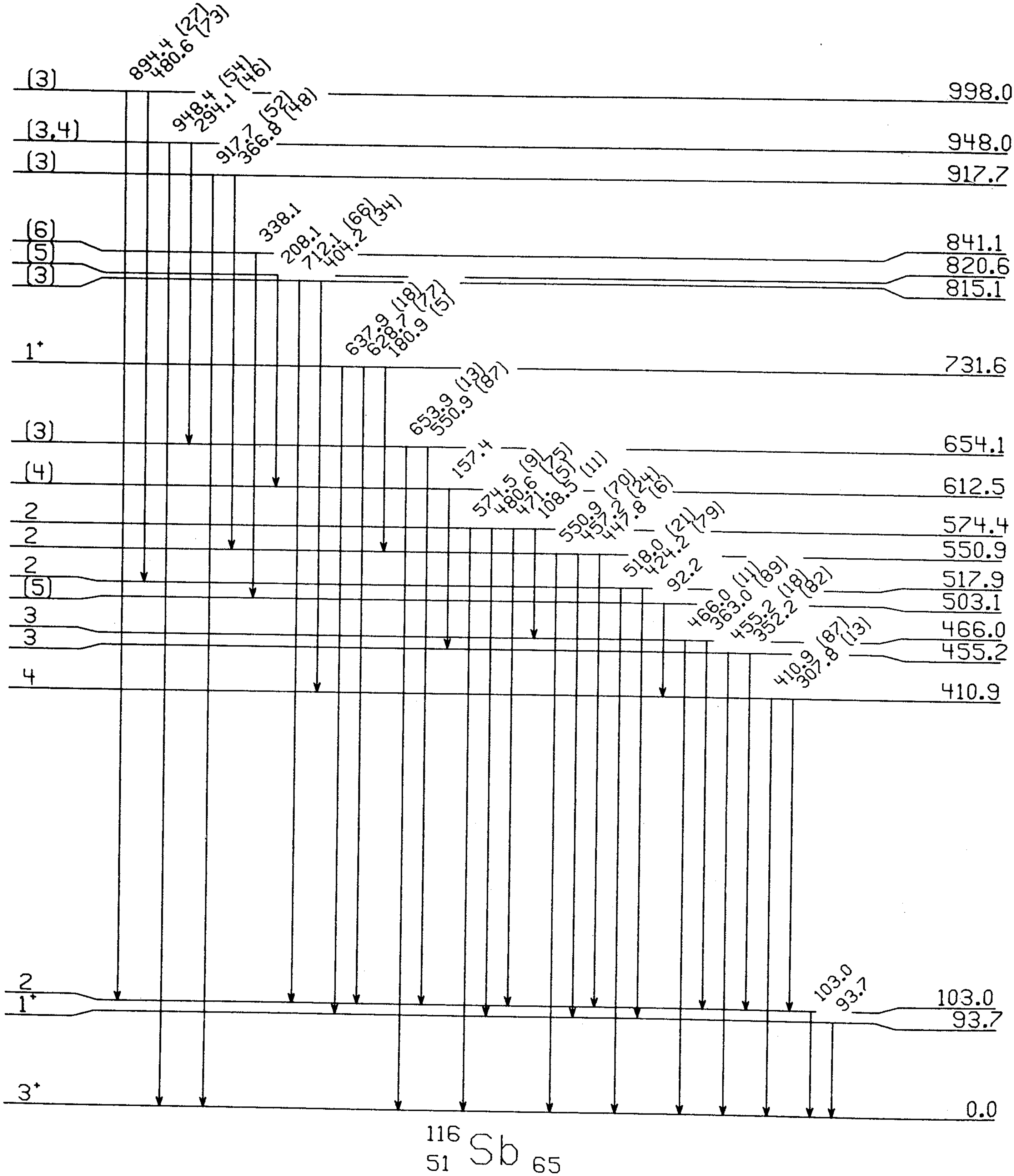

Fig. 2.--States below 1 MeV of excitation in ^{116}Sb.

function data using the (p,nγ) reaction were taken from below threshold to 1.0 MeV of excitation in 50 keV steps, and from 1.0 MeV to 1.5 MeV in 100 keV steps. Analysis of these data gives growth curves for the γ transitions and branching ratios for level depopulation. The curves are then related to the spins of the states through the Hauser-Feshbach formalism using a modified version of the code MANDY.[5]

Coincidence data have been taken at excitations of 1.0, 1.8, 2.5, 2.9, 6.2 MeV. Out of nearly a hundred gamma rays which appear to belong to the de-excitation of ^{116}Sb, less than 50 appear in the coincidence data. Most of the remaining γ rays are either not in coincidence or are too weak to appear.

Lifetime measurements using a beam sweeping system indicate that only the 93.7-keV transition is delayed by more than one or two nanoseconds. This lifetime is considerably longer than 0.5 μsec, which is the maximum time duration between successive swept cyclotron beam bursts using our old system. A new beam pulsing system is now in operation which will allow measurement of this lifetime in the near future.

Angular distribution data have been taken at excitation energies of 400, 750, 1150, and 1830 keV. The data, except for that at 1830 keV, are currently being analyzed using the program MANDY.[5]

From these data, and the previous values of $J^{\pi}=3^+$ for the ground state and 1^+ for the 94-keV state,[6] we can now make definite spin assignments for eight states plus tentative assignments to several others.

The electron-capture decay of the 2.5-hour 0^+ ground state of ^{116}Te has been investigated very briefly. Half lives and energy measurements indicated that three levels seen in the (p,nγ) experiments are fed by the beta decay. Eight or more γ-ray transitions are seen in the beta decay. Additional experiments using our Compton suppression system and measurements of γ-γ coincidences are planned to obtain additional information on the ^{116}Te beta decay scheme.

Fig. 2 is a preliminary and incomplete decay scheme which differs somewhat for the low energy states from that given in last year's report. Primarily, the state at 25.4 keV has been removed. This change resulted from a thorough analysis of additional coincidence data taken in the meantime. Included are the spin assignments that have been determined to date.

Two Rotational Bands in ^{182}Re

The rotational band structure of ^{182}Re is being studied by the (α,3nγ) reaction on a 4 mg/cm^2 ^{181}Ta target. γ-γ coincidences, γ-ray lifetimes, and γ angular distribution measurements have been performed and the analyses are being made. Coincidence data were taken with 4.5%- and 7%-Ge(Li) detectors (efficiency is given at 1333 keV relative to a 3 x 3 NaI(Tl) detector). The rotational band structure is quite evident in the integral coincidence spectra. A tentative decay scheme consisting of the first two rotational bands that have been identified is shown in Fig. 3. This can be compared with Refs. 7 and 8.

The γ-lifetime measurements were made with the cyclotron beam sweeper and a low energy Ge(Li) detector. Ten successive spectra were taken with each counted for 54 nsec. and the results analyzed. Two representative decay curves are shown in Fig. 4. The entire upper band is found to be delayed by 60 ± 4 nsec., being fed by what is probably a four quasi-particle isomer at 2256.6 keV via transitions of 647.3 and 344.6 keV. On the basis of the coincidence data this isomeric level was originally thought to be a member of the rotational band, but a plot of $E_I-E_{I-1}/2I$ vs. $2I^2$ (Fig. 5) shows such an interpretation inconsistent with theoretical predictions of rotational band structure.

The coincidence data were also analyzed by setting the TAC gate off the prompt peak so that those transitions which populate isomeric states would be accentuated. From this analysis we have tentatively concluded that the isomer is fed by transitions of 268.0 and 358.3 keV, respectively.

We have tentatively assigned spins of 7^+ and 9^- to the ground and upper bands respectively. The states of ^{182}Re are formed by a coupling of the odd proton and odd neutron outside the even-even core. The odd proton in ^{181}Re is $5/2^+[402\uparrow]$ and the odd neutron in ^{181}W is $9/2^+[624\uparrow]$ which can most easily couple to form spin 7^+ for the ground state. If the ground band has spin 7 one would expect the upper band to have spin 9 since its bandhead, the 443.1 keV level, feeds the 8^+ member of the ground band via the 289.0 keV transition. This bandhead could result from the promotion of a $9/2^-[514\uparrow]$ proton coupling to the $9/2^+[624\uparrow]$ neutron resulting in a spin and parity of 9^-. On this basis the isomer is expected to have a spin of at least 15.

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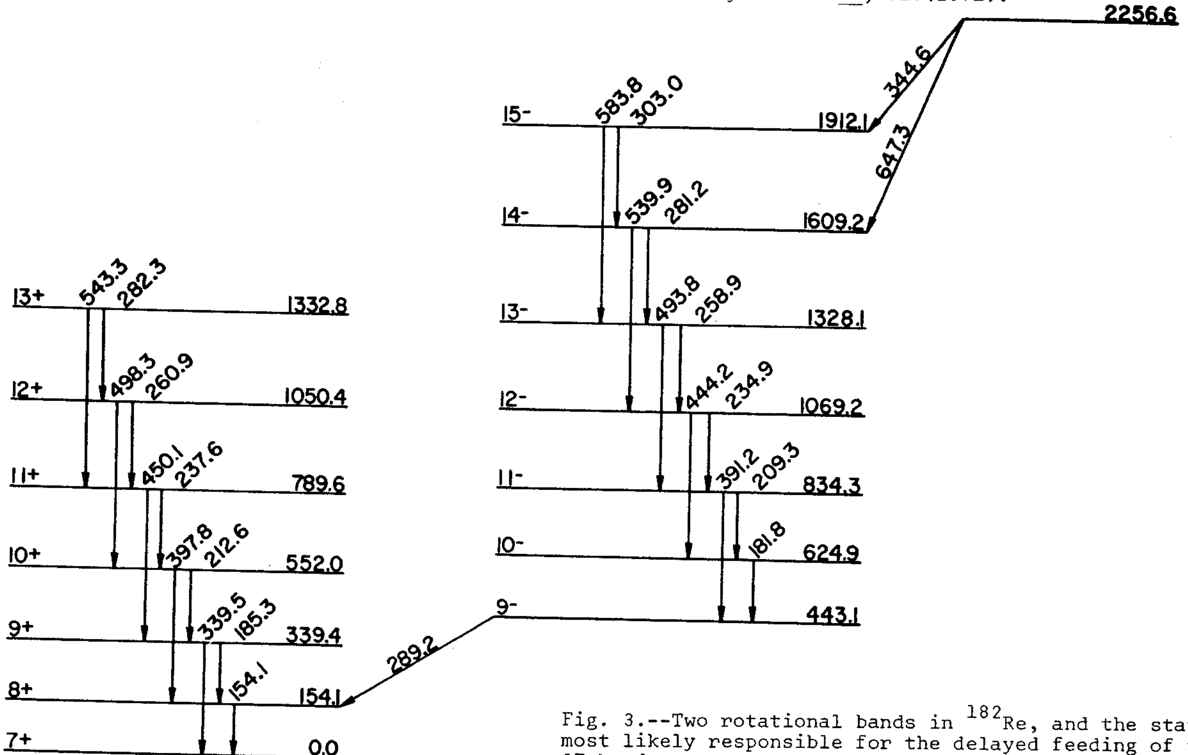

Fig. 3.--Two rotational bands in ^{182}Re, and the state most likely responsible for the delayed feeding of the 9^- band.

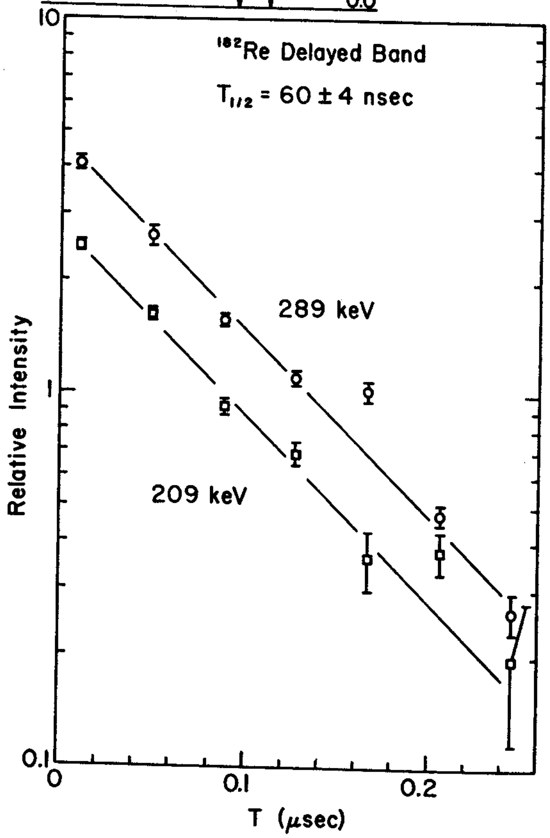

Fig. 4.--Data used to determine half-life of delayed component of 9^- band.

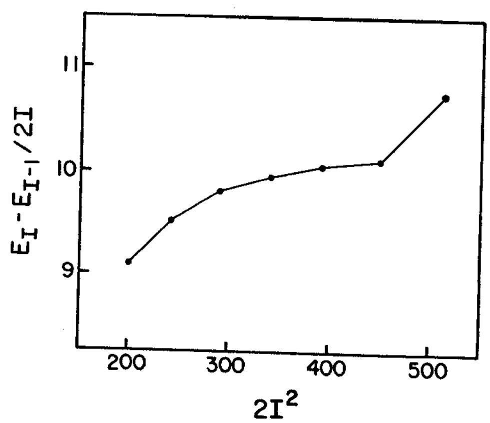

Fig. 5.--Rotational constant versus mean square angular momentum for each cascade M1 transition in the ^{182}Re 9^- band. The extreme upper left point results from an attempt to place the 344.6-keV transition in the same band.

Decay of N=79,81 Neutron Deficient Odd-Odd Rare Earths

R. B. Firestone, R. A. Warner, K. L. Kosanke, Wm. C. McHarris, and W. H. Kelly

Although the nuclear spectroscopy group has been quite active in the study of odd-A N=79,81 nuclei, relatively little effort has been put into the other nuclei in this region. The even-A nuclei yield relatively little β decay information, but the odd-odd nuclei should yield important information about core contributions to the decay. In the past, a 3-quasiparticle formalism has been used to describe the decay of odd-A nuclei to certain states. It is becoming evident from odd-odd decays that this description is often too simplistic.

In the simplest shell model picture the decays of the odd-odd nuclei of interest procede in the form $(\pi d_{5/2})(\nu d_{3/2}) \rightarrow (\nu d_{3/2})^2$. These decays are seen to procede with log ft values in the range 4.3-4.6. Additional decay is also seen to higher lying levels, particularly the lowest 2^+ and 0^+ vibrational states. The systematics of the odd-odd decays are shown in Figure 1. It should be noted that log ft values as low as 4.7-5.6 are seen to the excited states, and these decays involve a large core-coupled vibrational component. It has been assumed that many of the odd-A decays involve transitions to 3-quasiparticle levels and this is reconciled with the odd-odd systematics if we realize that single phonon vibrational states can be described as linear combinations of 2-quasiparticle states. The 3-quasiparticle states are really vibrationally coupled single particle states, and may be adequately described as a 3-quasiparticle states only if one component of the vibrational state is dominant.

Work on some of the odd-odd nuclei is already partially completed,[1-4] and we have recently looked at ^{144}Eu decay.[5] Work on ^{142}Eu and N=77 odd-odd nuclei as well as continuation of the other odd-odd nuclei in this region is in progress.

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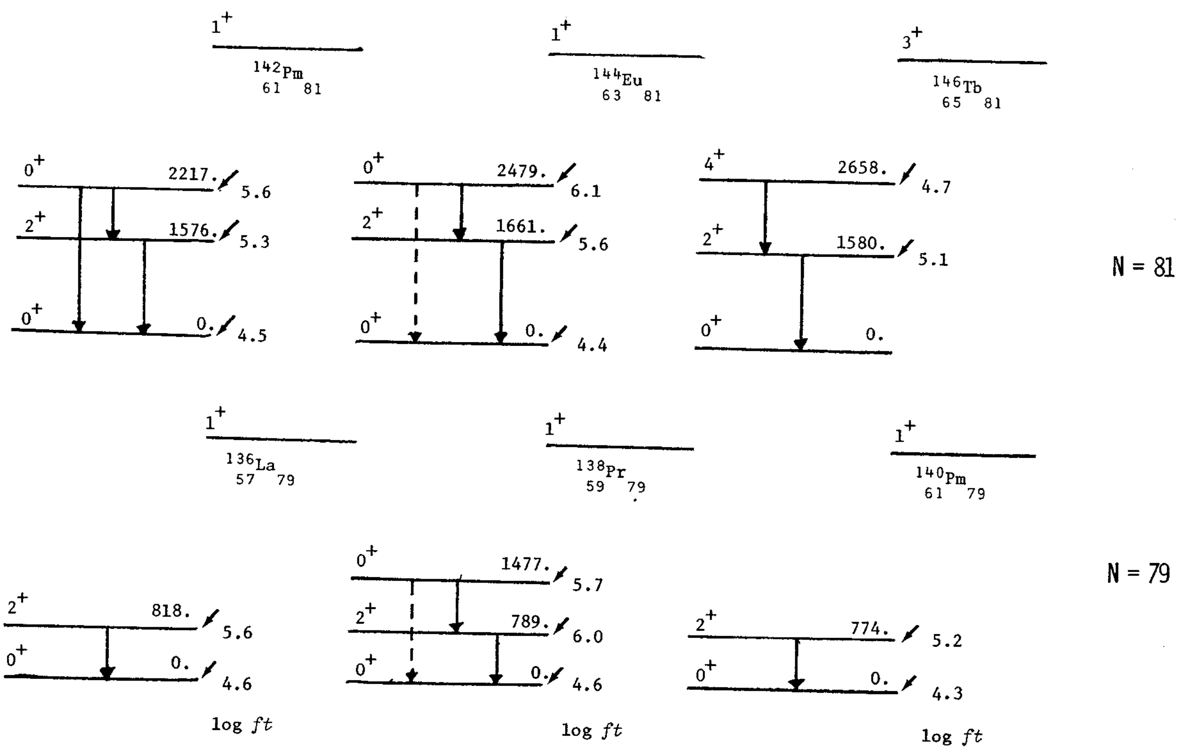

FIG. 1.--β decay systematics of odd-odd, N=79,81 nuclei. Dotted transitions are as yet unobserved E0 transitions.

The ε/β^+ and Delayed Proton Decay of $^{143g\&m}Gd$

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Continuing studies of the A=143 decay chain have led to the study of the new isotopes $^{143g+m}Gd$. Up until this point no information was available on these decays except for the suggestion of a half-life less than 1 min. We produced $^{143g+m}Gd$ by the $^{144}Sm(^3He,4n)$ reaction with 52 MeV ^3He on a 95% enriched $^{144}Sm_2O_3$ target. The activity was collected with a He-Jet transport system[1] with programmable paper tape advance.

42 transitions were assigned to ^{143m}Gd decay and 4 transitions to ^{143g}Gd. Because of the high angular momentum transferred in the reaction, the metastable state predominates and weak ^{143g}Gd transitions may be unobservable. These transitions are assigned on the basis of half-life and coincidence information. In Figure 1 half-life plots for $^{143g+m}Gd$ are presented. The half life of ^{143g}Gd is 39 ± 2 sec and that of ^{143m}Gd as 112 ± 2 sec.

Figure 2 presents a decay scheme for ^{143m}Gd and Figure 3 shows the decay scheme for ^{143g}Gd. The dotted transitions are confirmed by coincidence data, and log ft values are based on the estimated Q-value of 6.5 MeV. The $1/2^+$ ground state of ^{143g}Gd is tenuous but follows from systematics, and the spins of the first three states in ^{143}Eu are based partly on systematics. The fact that the 389.35 keV $11/2^-$ state is not seen in coincidence is consistent with the 1 msec half life ascribed to it. Theoretical internal conversion coefficients account accurately for the total input γ-ray intensity to the $7/2^+$ level.

Since mass calculations indicate that ^{143}Eu states above $\simeq 2.64$ MeV are unstable against proton decay, and γ-deexcitation has not been observed from levels above that energy, a search was made for β-delayed protons. Fig. 4 is a proton spectrum collected in 3 hrs. using a particle telescope in conjunction with the HeJRT system. From this spectrum an upper limit on proton emission has been placed at $\simeq 1$ in 10^5 ^{143}Gd β^+ decays, indicating that no correction is necessary for the log ft's in Figures 2 and 3.

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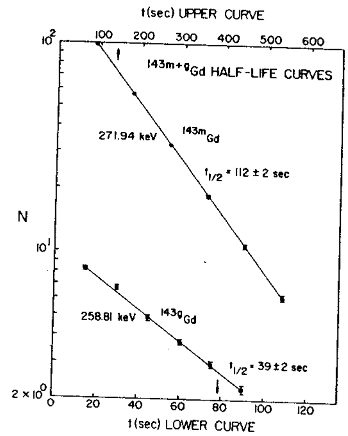

FIG. 1.--^{143g}Gd(lower line) and ^{143m}Gd(upper line) half-life data.

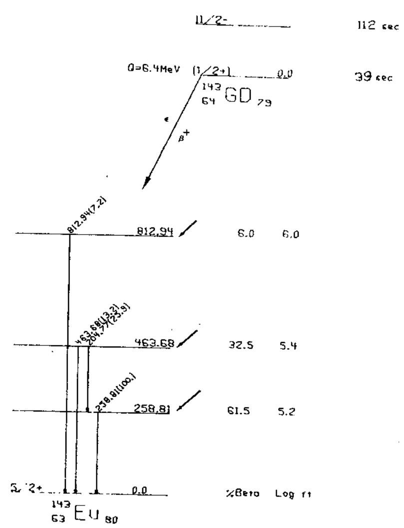

FIG. 3.--Decay scheme for ^{143g}Gd.

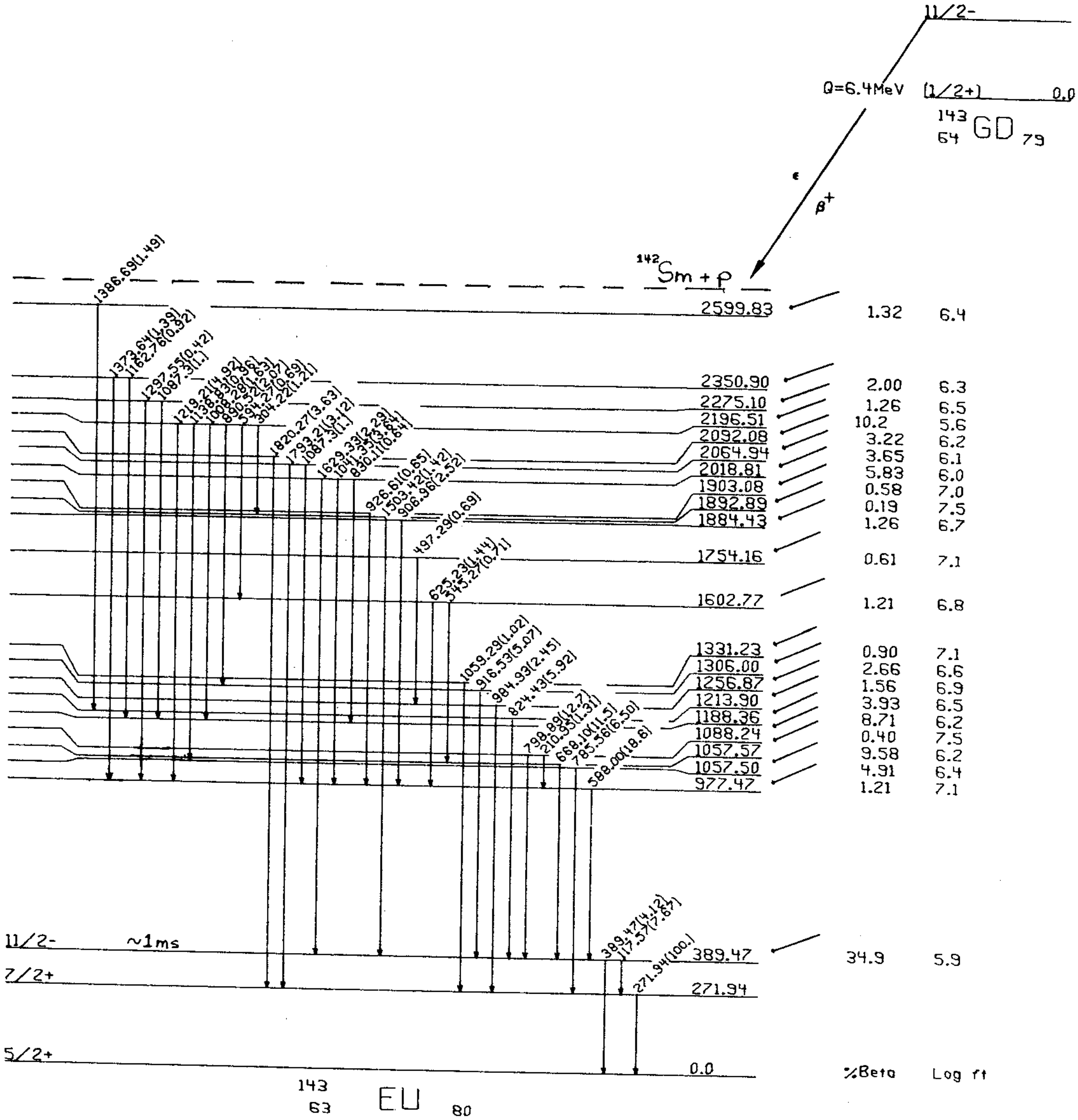

FIG. 2.--Decay scheme for ^{143m}Gd.

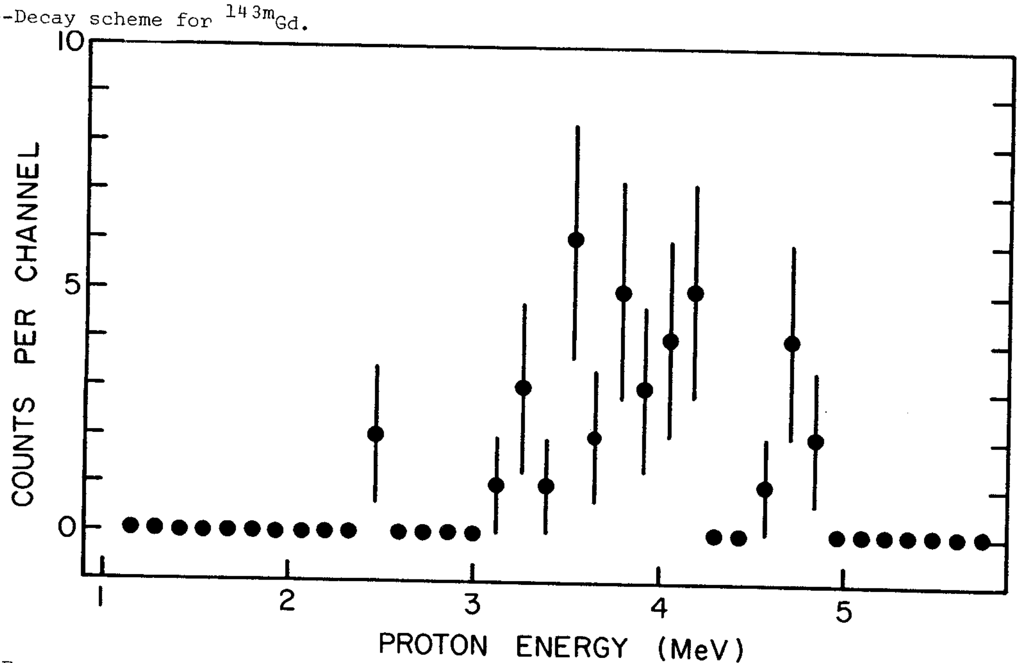

FIG. 4.--Energy spectrum of β-delayed protons accompanying ^{143}Gd decay.

Anomalous K/L Capture Ratios

R. B. Firestone, R. A. Warner, Wm. C. McHarris, and W. H. Kelly

An extensive study of ε/β^+ decay branching ratios was published recently by these workers.[1] Two striking anomalies were found, one each in ^{145g}Gd decay and ^{143g}Sm decay. The former anomaly differed from theory by a factor of 24 and the latter by a factor of 5. These results are presumed to be evidence of the dominance of higher order terms in the allowed matrix element.

The ^{145g}Gd decay data included both x-γ and β^+-γ coincidence results. From this work it is possible to infer the singles γ-ray intensities for comparison with measured singles intensities. These results are presented in Table I. The anomalous transition to the 808.5 keV level in ^{145}Eu appears to be missing some coincidence intensity, as well as the slightly anomalous transition to the 1041.9 keV level. This difference is beyond experimental error, but it could be explained by the fact that only K capture was measured while higher modes (L,M,...) were theoretically corrected for.[2] It is well known that in forbidden β decay higher modes of capture (L,M, etc.) can be far more significant than in allowed decay.[3] Presumably this fact is also true for higher order corrections to allowed decay. Assuming that all of the missing singles intensity belongs to electron capture, the predicted K/L+M... ratios are presented in Table I. This increased electron capture decay will tend to further increase the ε/β^+ branching ratios.

Experiments are currently in progress to measure the K/L capture ratios in ^{145g}Gd decay. X-γ coincidence experiments using a thin window Ge(Li) detector to gate both K and L lines should unambiguously solve this problem. Similar results will also be sought for in ^{143g}Sm decay where a similar anomaly is suspected.

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TABLE I.--Anomalous K/L+M+... Ratios in ^{145}Gd Decay.

	Singles(%)		ε/β^+		K/L+M+...	
Level	Coincidence	Measured[4]	Theory[5]	Experiment	Theory[2]	Predicted
808.5	3.30	5.13	0.45	10.7±2.0	5.89	1.15
1041.9	8.74	9.93	0.60	0.72±0.05	5.88	1.99

Decay of 4.7-h ^{160m}Ho to Levels in ^{160}Dy

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Work has begun in our laboratory on the complex decay of ^{160m}Ho to ^{160}Dy. The ^{160m}Ho is produced by the $(\alpha,3n)$ reaction on ^{159}Tb and the resulting activity is allowed to decay for several hours to allow equilibrium to be established between the 4.7-hour, $I^{\pi}=(2^{-})$ isomeric state in ^{160}Ho and the 26-min, $I^{\pi}=(5^{+})$ ground state.

The EC-β^{+} decay of ^{160m}Ho is unusually interesting, because the spins of the β-decaying ground and isomeric states allow a wide variety of states in the daughter ^{160}Dy nucleus to be observed, in principle ranging from $I^{\pi}=0^{+}$ to $I^{\pi}=7^{-}$. This situation offers unique prospects for extracting from the decay an unusual quantity of information on nuclear structure.

At this writing, more than 200 γ-rays, have been assigned to the ^{160m}Ho decay spectrum. Work on the construction of a preliminary decay scheme is underway.

Quasiparticle States in Deformed Nuclei

T. L. Khoo, G. F. Bertsch, and G. Hamilton

The quasiparticle states in deformed nuclei provide simple systems for studying the effects of the residual nucleon-nucleon interaction, in a manner somewhat analogous to that provided by states of near magic odd-odd nuclei.[1] This is especially true if high K configurations are considered since these are, in general, quite pure. In few quasiparticle structures, only a limited number of interactions need be considered. For instance, for a 4 quasiparticle state only 6 interactions between the different pairs of nucleons are involved. The energy of such a state is given by

$$E_{4qp}=E_1+E_2+E_3+E_4+\sum_{i<j} V_{ij} \text{ (6 terms)}$$
$$= (E_1+E_2+V_{12})+(E_3+E_4+V_{34})+\sum_{i<j} V_{ij}\text{(4 terms)}$$
$$= E^{12}_{2qp}+E^{34}_{2qp}+\sum_{ij} V_{ij}\text{(4 terms)} \qquad (1)$$

where E_i is the individual quasiparticle energy, V_{ij} is the interaction energy between nucleons i and j, and E^{kl}_{2qp} is the energy of the 2 quasiparticle state with nucleons k and l. The individual quasiparticle energies are difficult to calculate accurately; however, as shown in Equation 1, one needs only to know the experimental energies for the appropriate 2 quasiparticle states.

The present calculations are an extension of our previous study[2] of the residual neutron-proton interaction which gives rise to the mixing between neutron and proton 2 quasiparticle configurations.[3] The methods used have already been outlined in Reference 2.

An example of a 4 quasiparticle state is the $K=12^+\{7/2(404)_p\ 5/2(402)_p\ 7/2(514)_n\ 5/2(502)_n\}$ state in ^{176}Hf at an energy of 2.83 MeV (See T. L. Khoo et al., this report). From the known[3] two quasiparticle energies,
$E^{7/2p\ 5/2p}_{2qp}+E^{7/2n\ 5/2n}_{2qp}=3.09$ MeV,
we deduce that the four proton-neutron interactions provide -0.26 MeV. The calculated interaction with a δ-function force adjusted to band splittings in odd-odd nuclei is -1.34, which is ~1 MeV lower than the observed. We have also performed calculations using matrix elements derived from the Reid potential and obtain $E_{K=12^+}$ = 1.44 MeV, again a value which is too low. In general, the calculated energies of all multi-quasiparticle states is much lower than the experimental ones, indicating that the effective neutron-proton interaction in 3 or 4 quasiparticle states is much less attractive than in 2 quasiparticle states.

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High K 2- and 4- Quasiparticle States in ^{174}Hf and ^{176}Hf

T. L. Khoo, F. M. Bernthal, J. S. Boyno, and R. A. Warner

The level density of high K states in deformed nuclei is, in general, lower than that of low K states. Furthermore, the interactions between high and low K configurations is very small, so that although the high K states may be embedded at high excitation in a sea levels, they usually remain rather pure. Therefore, from a theoretical stand-point, it is attractive to study these high K systems. Such states also offer advantage from an experimental viewpoint: the lowest high K states are isomers, thus simplifying their identification, while the higher ones decay through the lower isomers and hence may be isolated by delayed coincidence techniques. Finally, with few quasiparticle structures there are only a small number of nucleon-nucleon interactions to consider and it is the eventual aim of this study to examine the effects of the residual interaction on the 2- and 4- quasiparticle configurations in ^{174}Hf and ^{176}Hf.

Gamma rays from the ^{172}Yb(α,2n) ^{174}Hf, ^{174}Yb(α,4n) ^{174}Hf and ^{176}Yb(α,4n) ^{176}Hf reactions have been observed with various appropriate alpha beam energies and at different detection angles in order to obtain excitation functions and angular distributions. Extensive γ-γ coincidence data have also been accumulated. In addition, delayed γ-rays have been observed for periods ranging from 0.5-5000 μsec following beam irradiation by using the beam pulser described elsewhere in this report. In both (α,4n) reactions a large number (25-35) of delayed γ-rays were observed.

A) ^{174}Hf

In ^{174}Hf, we have established the rotational band members (up to spin 12 or 13) based on a $K=6^+$ state at 1549.3 keV, a $K=8^-$ state at 1797.4 keV and a $K=(4^+)$ state at 1713.5 keV. The $K=6^+$ and $K=8^-$ levels are isomers with half lifes of 2.4±.2 and 2.39±0.04 μsec., respectively. The $K=6^+$ band is almost pure (89%) two quasiproton {$7/2^+(404)$, $5/2^+(402)$}, in contrast with the analogous state in ^{176}Hf which is almost completely mixed with a two quasi-neutron configuration.[1] Two 4 quasiparticle isomers have also been identified at 3269 and 3312 keV with tentative K assignments of (12^-) and (12^+) and half-lifes of 3.9±0.3 and 3.7±0.2 μsec., respectively. Possible configurations for these states are $K=12^-${$7/2(404)_p$ $5/2(402)_p$ $7/2(633)_n$ $5/2(512)_n$} and $K=12^+$ {$7/2(404)_p$ $5/2(402)_p$ $7/2(514)_n$ $5/2(512)_n$}. In addition to these high K states, the ground and β-bands have also been identified to spins 18 and 16, respectively.

B) ^{176}Hf

Many of the high K 2 quasiparticle structures have been previously identified.[1] In this work we have concentrated on the identification of two 4 quasiparticle isomers at 2827 and 2866 keV, which both decay through two $K=8^-$ bands with half-lifes of 234±20 and 211±4 μsec., respectively. The decay of the isomers are consistent with tentative assignments of $K=12^+$ {$7/2(404)_p$ $5/2(402)_p$ $7/2(514)_n$ $5/2(512)_n$} and $K=14^-$ {$7/2(404)_p$ $9/2(514)_p$ $7/2(514)_n$ $5/2(512)_n$}.

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On Setting Limits to the Hexadecapole Deformations in W and Os Nuclei from Perturbed Rotational Band Structure*

F. M. Bernthal, D. B. Jeltema, J. S. Boyno,
T. L. Khoo, and R. A. Warner

In recent months, at least two groups have reported measuring very large electric hexadecapole transition moments for nuclei in the W-Os region.[1,2] These results, based on Coulomb excitation measurements carried out with alpha particles, imply static nuclear hexadecapole deformations that appear to be in serious disagreement with the nuclear charge distribution derived from the muonic x-ray data of Davidson, et al.[3] and in substantial disagreement with the nuclear inelastic scattering result of Hendrie.[4]

The implication of large values of the nuclear hexadecapole deformation for interpreting (d,t) and (^{3}He,α) transfer reaction cross-sections for populating states in ^{181}W and ^{183}W has been dealt with by Casten in a recent letter.[5] Casten suggests that the distinctive ℓ=6 cross-section patterns can be explained by any of a wide range of ε_4 values ($0.06 \leq \varepsilon_4 \leq 0.16$). It is not possible however to set definite limits on the hexadecapole deformation from the ℓ=6 transfer data alone, because the projection quantum numbers cannot be assigned.

In addition to the transfer reaction data, there has also recently accumulated a substantial quantity of data on the so-called "parity-unique" $i_{13/2}$ rotational band structure in the odd-A W and Os isotopes. We have shown that the experimental data on even-parity rotational and intrinsic states in ^{181}W and ^{187}Os are consistent only with the smaller hexadecapole deformations ($\varepsilon_4 \cong 0.06$) predicted by Nilsson, et al.[6] and deduced by Hendrie[4] ($\varepsilon_2 \cong 0.23$, $\varepsilon_4 \cong 0.08$) from nuclear inelastic scattering on ^{182}W.

The primary data for this consideration are those derived from (α,3$\eta\gamma$) reactions on targets of ^{180}Hf and ^{186}W. The irradiations were carried out using α-particle beams from the MSU cyclotron. Attention is here focused on the even-parity band structure of ^{181}W and ^{187}Os.[7]

The procedure used to fit rotational band structure in deformed odd-A nuclei is by now standard and reasonably well understood.[8] The rotational and intrinsic levels based on the predominately $i_{13/2}$ Nilsson states known from (α,xnγ), decay, and transfer reactions have been fitted for three different sets of parameters:

(1) The ε_2 and ε_4 values suggested by the calculations of Nilsson, et al.[6]

(2) Deformations which correspond to those implied for ^{182}W and ^{186,188}Os by conventional analysis of E4 moments obtained from Coulomb excitation data.[1,2]

(3) Deformations which correspond approximately to the lower limit of the errors on ε_4 implied by the E4 moment analysis for ^{182}W and ^{186,188}Os.

The results of the band-fitting calculations for ^{181}W and ^{187}Os are summarized as follows: The experimental level energies are easily explained if one assumes an input quasiparticle spectrum that corresponds to $\varepsilon_4 \cong 0.06$, but it is impossible to fit the experimental data with any reasonable parameter set if $\varepsilon_4 \gtrsim 0.08$. This is in qualitative agreement with the conclusions of Ogle, et al.[9] in their study of single particle levels in a deformed Woods-Saxon potential.

We conclude that the spectroscopic data in the odd-mass W and Os nuclei are incompatible with tetroidal deformations as large as those recently reported for ^{182}W and seemingly also implied for ^{186,188}Os. It thus seems appropriate that further research on the problem be concentrated on reconsidering the origins and implications of the large measured E4 transition moments in the W and Os region of the nuclear chart.

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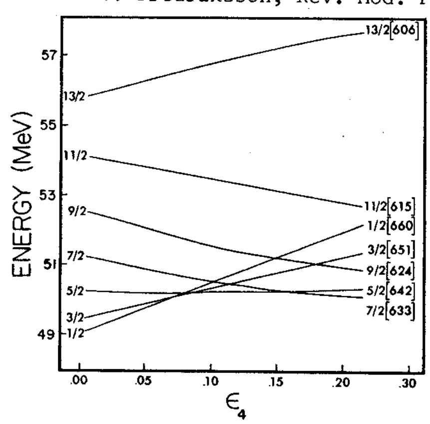

Fig. 1.--The $i_{13/2}$ Nilsson orbitals as a function of hexadecapole deformation, ε_4. Parameters ε_2, μ, and κ are for ^{182}W.

Decoupled $i_{13/2}$ Neutrons and Backbending in Rare-Earth Nuclei

F. M. Bernthal, J. S. Boyno, T. L. Khoo, and R. A. Warner

The discovery in 1972 of the so-called "backbending" effect[1] in the yrast band structure of even-even rare earth nuclei prompted an initial interpretation that the data confirmed the breakdown of nuclear superfluidity at high spins, an effect proposed ten years earlier by Mottelson and Valatin.[2] More recently however, Stephens and Simons[3] (SS) proposed that the observed effect could be explained in a much simpler, albeit related way, as arising from the recoupling of a single pair of $i_{13/2}$ neutrons in a "rotation-aligned" coupling scheme. If indeed the $i_{13/2}$ neutrons nearest the Fermi surface are primarily responsible for the backbending effect, it seems clear that the high-spin behavior of these neutrons in odd-N nuclei should provide a picture of what to expect in the neighboring even-even nuclei, i.e., the tendency of the odd $i_{13/2}$ neutron to decouple from the nuclear core rotation should be a direct measure of the ease with which a similar configuration could be achieved in even-even nuclei.

An analysis of the particle-core decoupling in odd-neutron $i_{13/2}$ rotational bands places the backbending phenomenon in the even-even Os nuclei[4] squarely within the domain of the SS model, and in fact can account for all such effects so far observed in the rare-earth deformed region with the possible exception of the ^{170}Yb case.[5]

We have evaluated the expectation values for $\vec{R}^2$ as a function of spin in several odd-N nuclei. Here, R is the core rotational angular momentum. The numerical work becomes particularly simple if one first transforms the odd-A wave functions to the $|IRj\rangle$ representation suggested by Vogel.[6] The overlaps of the wave functions in this new representation with those in the conventional $I\Omega$ representation are formed, and

$$\langle \vec{R}^2 \rangle = \sum_{R,j} \langle IRj\,|IM\rangle^2\, R(R+1)$$

One is thus provided with a simple criterion for estimating the degree of particle-core decoupling in the several even-parity bands of interest. Fortunately, most of the available data span the region of greatest interest, i.e. those nuclei where a transition between backbending and normal behavior seems to occur. In Fig. 1 we show the quantity $[\langle\vec{R}^2\rangle - \langle\vec{R}^2_{dec}\rangle]$ plotted as a function of spin for selected cases of interest. Here, R^2_{dec} is just the decoupled limit; in that limit, the quantity plotted should approach zero.

Though additional data would be desirable for the more neutron-rich isotopes of the lower-Z rare-earths, the picture emerges rather clearly that the regions of backbending nuclei are in general characterized by rotation-particle decoupling in the neighboring odd-A $i_{13/2}$ band structure. The principal difference between the conclusions of Fig. 1 and the more qualitative analysis presented in Ref. 7 is the clear inclusion in Fig. 1 of ^{187}Os and ^{179}W in the region of essential particle-core decoupling. Note also that ^{179}W and ^{159}Dy adjoin ^{180}W and ^{158,160}Dy, all three of which fail to meet the strict "backbending" requirement by only a few keV for at least one high spin state; the g.r.b. behavior of these three even-even nuclei is certainly anomalous.

In fact, the single difficulty in drawing a broad conclusion from Fig. 1 is the ^{170}Yb case. The appearance of "backbending" in the ground band of this nucleus is not so easily understood in the SS model. In view of the modest decoupling exhibited by the $i_{13/2}$ particles in ^{169}Yb and ^{171}Yb, it may well be that the ^{170}Yb g.r.b. singularity[5] arises from the influence of a more concerted pairing breakdown.

It thus appears that if decoupling of $i_{13/2}$ neutrons from the core rotation is indeed the explanation for "backbending" in the ground rotational band of even-even deformed nuclei, then that explanation can apply equally well to the neutron-deficient rare earth region where the backbending effect was first reported, and to the N = 106-110 region of W and Os isotopes which have also been shown to exhibit strong backbending behavior.[4]

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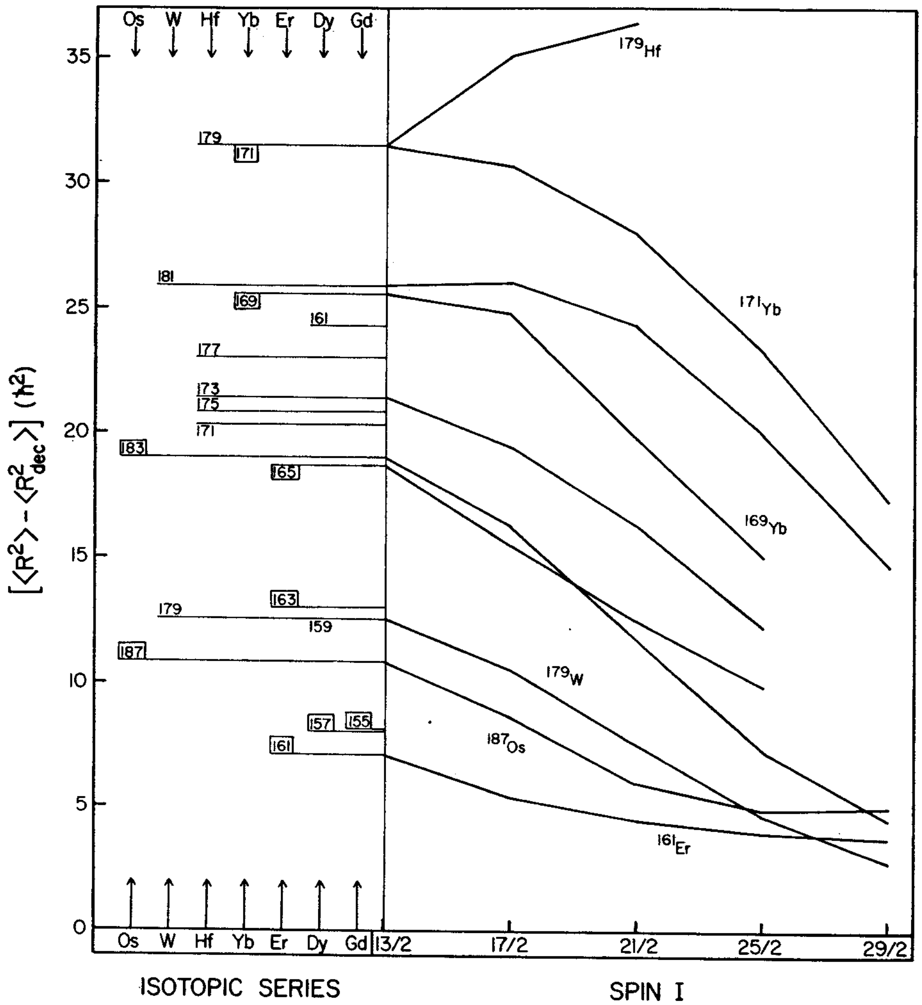

Figure 1.--The approach to rotation-particle decoupling for even-parity rotational bands in several odd-N rare-earth nuclei. Not all spins are plotted for all nuclei, but data for spin 13/2 are indicated on the left portion in each case. Mass-numbers in a box indicate backbending in at least one neighboring even-even isotope. $^{179,181}W$ and $^{183,187}Os$ data are from our laboratory; wave functions for all other nuclei are taken from references summarized in Ref. 7.

Levels of ^{177}W and ^{178}W

C. Dors, F. M. Bernthal, T. L. Khoo and C. King

Investigation has recently begun on the rotational band structure of the even-even rare earth nucleus ^{178}W and of the neighboring odd mass nucleus ^{177}W. This study was undertaken primarily to search for bands built on high-K states in ^{178}W in order to see if any mixing occurs between these bands which might provide further insight into the n-p residual interaction, and secondarily to complete a study on the odd mass nuclei in this region.

The ^{177}W was produced in the $^{177}Hf(\alpha,4n\gamma)$ reaction induced by bombarding a self-supporting $1mg/cm^2$ foil of ^{177}Hf with 48 MeV alpha particles from the MSU cyclotron. Extensive γ-γ coincidence data were taken in the range of 50 to 1300 keV. The analysis of these data is now in progress.

The $(\alpha,3n\gamma)$ reaction was used to populate states in ^{178}W. The ^{177}Hf target was bombarded with a 37 MeV alpha beam and γ-γ coincidences were recorded. The ground band has been identified to spin 16 and the $K=2^-$ octupole band to spin 12. Members of the ground band to spin 6 and the first three members of the octupole band had been previously seen[1] in the decay of ^{178}Re, and they are in good agreement with levels found from the in-beam data. A comparison of the ground band of ^{178}W with the ground bands of ^{180}W and ^{182}W is shown in Figure 1 which is a plot of $2\mathcal{J}/\hbar^2$ vs. $\hbar^2\omega^2$ for the appropriate transitions.

Delayed singles were also taken for this nucleus but no delayed transitions were found in the region 10 to 500 ns. Other measurements on ^{177}W and ^{178}W are in progress and the results will be reported in a forthcoming publication.

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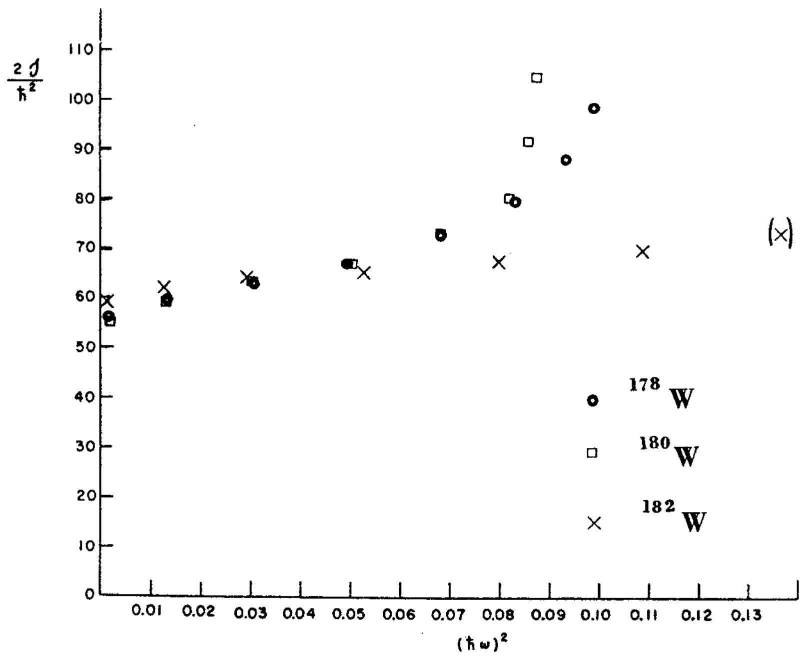

Levels in ^{182}W*

B. D. Jeltema, F. M. Bernthal, T. L. Khoo, and C. L. Dors

The study of excited states in ^{182}W populated via the $^{180}Hf(\alpha,2n)^{182}W$ reaction is nearing completion. A number of low-lying high-K rotational bands have been tentatively identified, and some properties of these bands have been investigated. In addition, the decay of ^{182m}Re to high spin states in ^{182}W was studied, as the in-beam data indicated that several errors existed in previous studies[1,2] of this decay. The level schemes deduced from in-beam and decay γ-γ coincidence data are not shown here due to their complexity, but the rotational bands assigned from the work are shown in Figure 1. The spins indicated as tentative are assigned only on the basis of the observed rotational band patterns. The ground state rotational band is seen tentatively up to $I^{\pi}=14+$, and a plot of $\frac{2I}{\hbar^2}$ vs. $\hbar^2\omega^2$ (Figure 2) shows that evidence for back bending behavior exists in the 14+ state. The rotational band built on the isomeric $K^{\pi}=10+$ state[5] was identified by setting a time gate on the delayed portion of the TAC and an energy gate on the 518.5-keV delayed γ-ray.

Timing experiments indicate that no isomeric states other than the $K^{\pi}=10+$ state are populated. The prompt decay out of the $K^{\pi}=6+$ band head (four orders K-forbidden) is believed to result from mixing with the $I^{\pi}=6+$ member of the γ band, which is believed to lie within 50 keV of the $K^{\pi}=6+$ band head.

Mixing between the three positive-parity collective bands of ^{182}W has been investigated by Günther, et al.,[3] and we have also studied this mixing, since the present study has revealed more states than was used in Gunther's analysis. The results of our calculations indicate that these levels cannot be described in terms of three-band mixing, and that at least one additional Low-K band is coupled to the collective bands. A plot of $\frac{E(I)-E(I-1)}{2I}$ vs. $2I^2$ (a trumpet plot) for the octupole bank is shown in Figure 3; the apparent odd-even shifts of the points is believed to result from Coriolis coupling with the K=0 octupole band through the K=1 octupole band. The anomalous point corresponding to the energy separation of the $I^{\pi}=5^-$ and 6^- states is a result of mixing with the $K^{\pi}=4^-$ two-quasineutron state. From the level structure of Figure 1, it is apparent that this mixing would cause the I=5 and 6 members of the octupole band to be pushed away from each other. Investigation of the properties of the ^{182}W rotational bands is still in progress.

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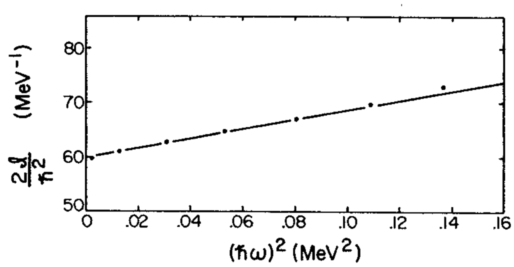

Figure 2

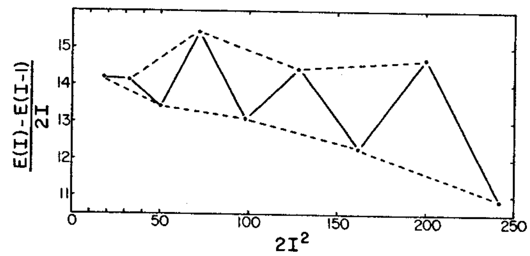

Figure 3

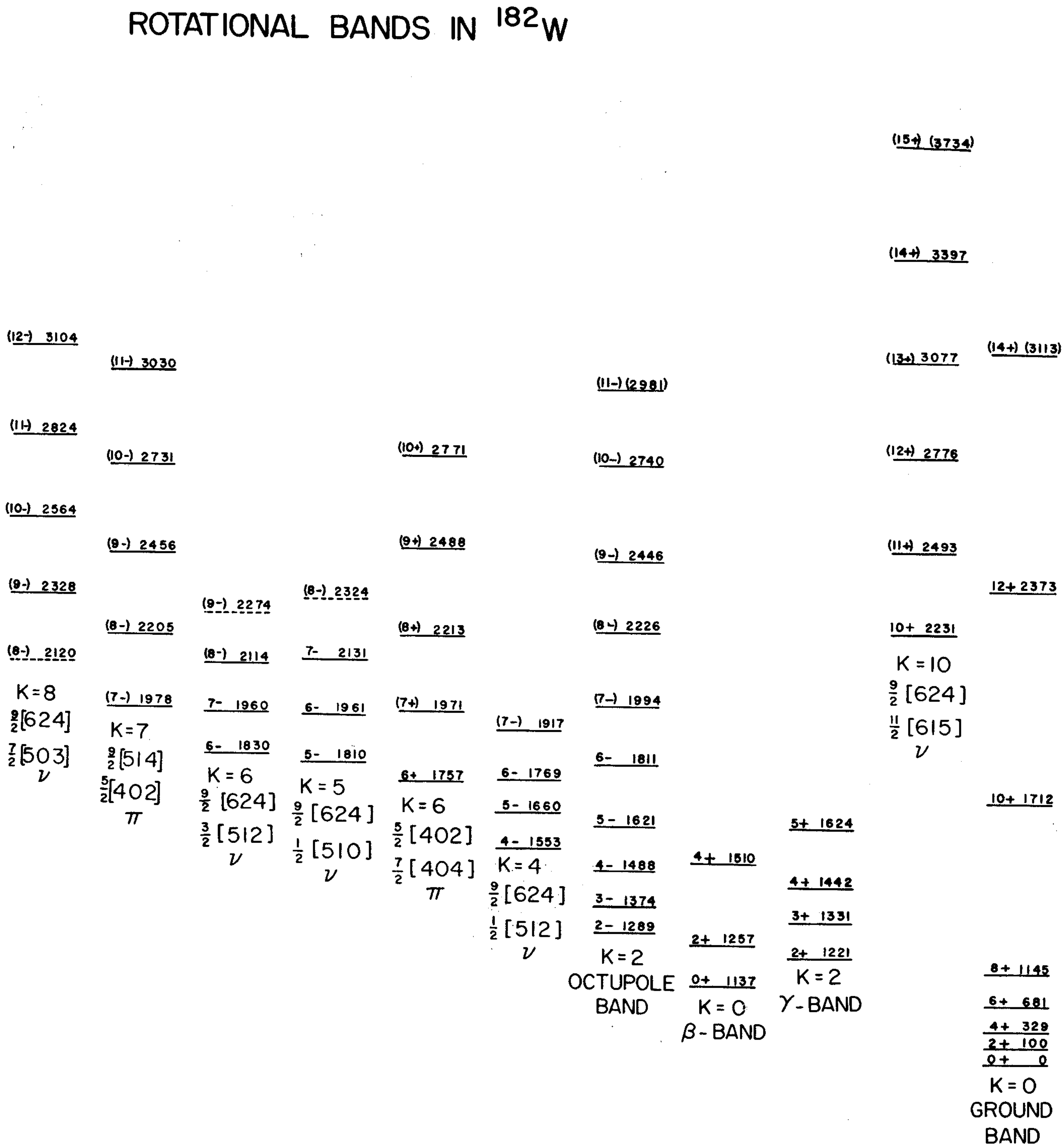
ROTATIONAL BANDS IN ¹⁸²W
(12-) 3104
(11-) 2824
(10-) 2564
(9-) 2328
(8-) 2120
K=8
9/2[624]
7/2[503]
ν
(11-) 3030
(10-) 2731
(9-) 2456
(8-) 2205
(7-) 1978
K=7
9/2[514]
5/2[402]
π
(9-) 2274
(8-) 2114
7- 1960
6- 1830
K=6
9/2 [624]
3/2 [512]
ν
(8-) 2324
7- 2131
6- 1961
5- 1810
K=5
9/2 [624]
1/2 [510]
ν
(10+) 2771
(9+) 2488
(8+) 2213
(7+) 1971
6+ 1757
K=6
5/2 [402]
7/2 [404]
π
(7-) 1917
6- 1769
5- 1660
4- 1553
K=4
9/2 [624]
1/2 [512]
ν
(11-) (2981)
(10-) 2740
(9-) 2446
(8-) 2226
(7-) 1994
6- 1811
5- 1621
4- 1488
3- 1374
2- 1289
K=2
OCTUPOLE BAND
4+ 1510
2+ 1257
0+ 1137
K=0
β-BAND
5+ 1624
4+ 1442
3+ 1331
2+ 1221
K=2
γ-BAND
(15+) (3734)
(14+) 3397
(13+) 3077
(12+) 2776
(11+) 2493
10+ 2231
K=10
9/2 [624]
11/2 [615]
ν
(14+) (3113)
12+ 2373
10+ 1712
8+ 1145
6+ 681
4+ 329
2+ 100
0+ 0
K=0
GROUND BAND

Figure 1

Rotational Bands in ^{183}Os

C. Dors, F. M. Bernthal, and R. A. Warner

We have studied the rotational band structure of ^{183}Os via in-beam γ-ray spectroscopy, and interpretation of the data is in the final stages. A preliminary level scheme is shown in Fig. 1. The 9/2+[624], 7/2-[514], and 1/2-[510] or [521] bands are displayed here. Only the crossover E2 transitions were seen in the 1/2-band. The bound band assignments are in good agreement with the work done in Stockholm by Lindblad, et al.,[1] and the first two members of the 1/2-band agree with preliminary ^{183}Ir decay data from Ladenbauer-Bellis, et al. at Yale.

The levels in ^{183}Os were populated in an (α,3nγ) reaction on ^{182}W and also by the (p,3nγ) reaction on ^{185}Re. The tungsten target was a 1 mg/cm^2 foil prepared from the separated isotope by G. Sletten at the Niels Bohr Institute. This target was bombarded with a 38-MeV beam of alpha particles from the MSU cyclotron. Singles spectra were taken with a LEPS germanium detector at five angles to confirm the assignments of the cascade and crossover transitions. Delayed singles in the region 10-500 nsec were taken using the beam sweeping system. Excitation function and γ-γ coincidence data further confirm the assignments.

The second reaction, a (p,3nγ) reaction, was performed on a target of ^{185}Re prepared by imbedding the Re powder in a thin layer of polystyrene. A beam of 28-MeV protons was used to populate the levels in ^{183}Os and the singles spectrum obtained which is shown in Fig. 2 was similar to the spectrum from the (α,3nγ) reaction except for a shift in γ-ray intensities. γ-γ coincidence and angular distribution data were also obtained for the (p,3nγ) reaction. Fig. 3 shows a coincidence spectrum from these data with the gate set at the 393-keV transition which is the 7/2-[514] bandhead to ground transition. Labeled in this spectrum are the first few members of the band built on the 393-keV bandhead.

The final analysis of these data is now taking place and may reveal some further placements of levels not yet in the level scheme. At this time, however, only about 60% of the gamma rays seen have been placed. The rest desperately need supportive decay work to aid in their assignment to the level scheme.

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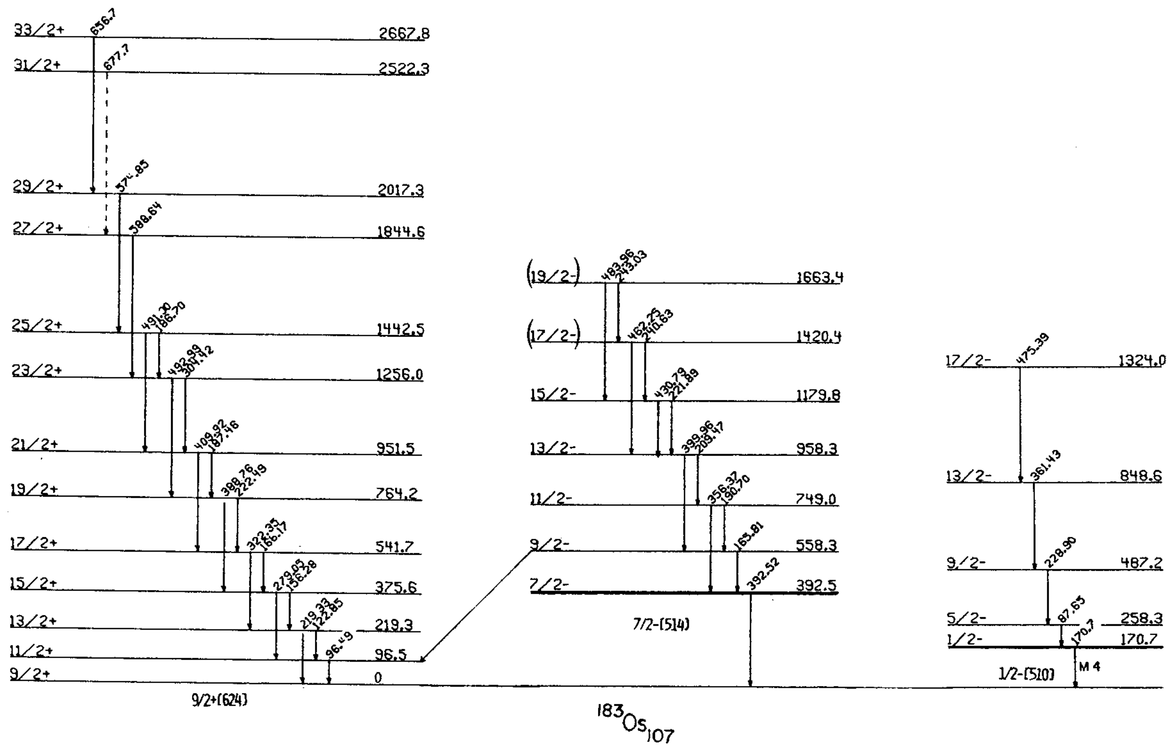

Figure 1

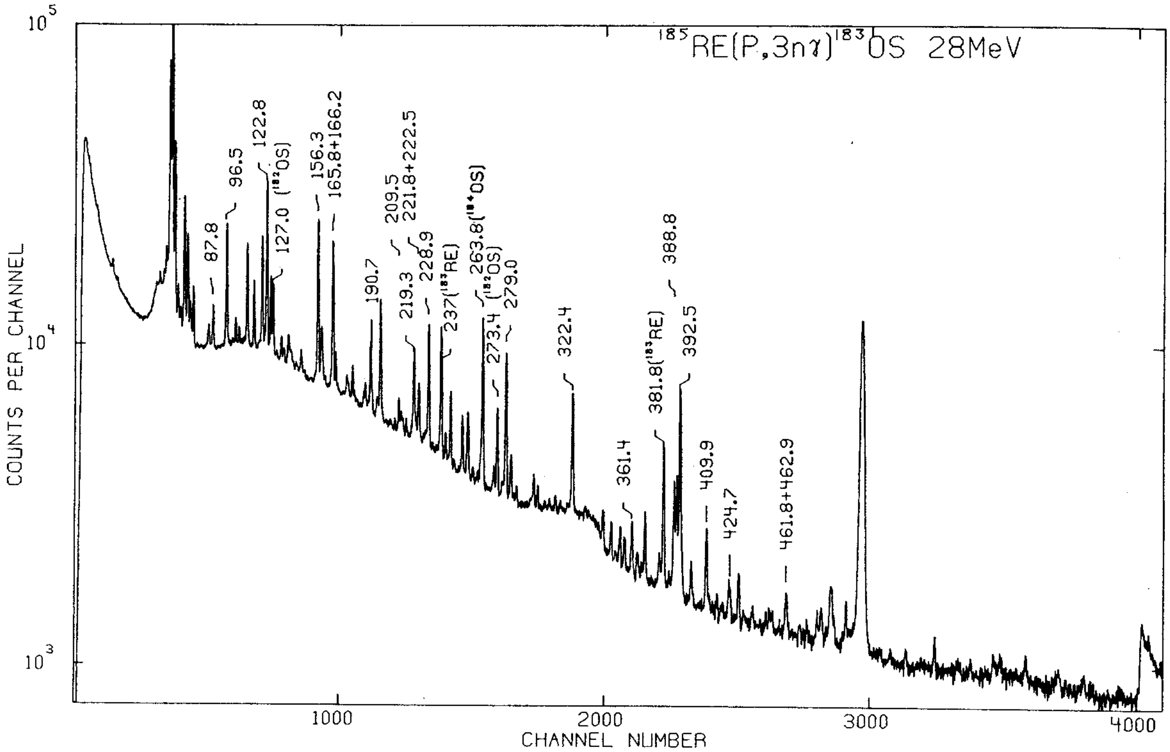

Figure 2

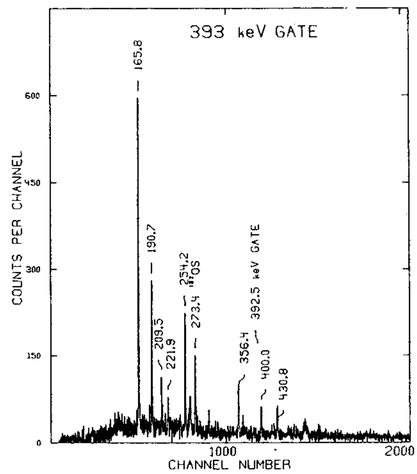

Figure 3

High Spin Level Structure in Pt Nuclei from Os(α,xnγ) Reactions

J. C. Cunnane, M. Piiparinen, and P. J. Daly
and
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An extensive series of experiments are in progress to elucidate the high-spin level structure of both even- and odd-mass Pt nuclei in the range A=186-194 by (α,xnγ) reactions on enriched Os targets. These experiments were stimulated by the evidence for backbending behaviour in the ground bands of Os nuclei obtained earlier in this laboratory,[1] by the discovery in Purdue Tandem studies of the systematic occurrence of 5^-, 7^-, 9^- ... level sequences in Pt and Hg nuclei[2] and by Berkeley and Julich results[3,4] for Hg nuclei, which can be elegantly explained in terms of rotation-alignment coupling. The fact that the Pt nuclei span the region in which the nuclear shape transition from prolate to oblate (or triaxial) is believed to occur lends additional purpose to these investigations.

The experimental techniques employed have included prompt and delayed γ-ray singles, prompt and delayed γ-γ coincidence, angular distribution and excitation function determinations. For the three nuclei ^{192}Pt, ^{190}Pt, and ^{188}Pt all the measurements have been completed, the analysis of the results is nearing completion and detailed level schemes incorporating much new spectroscopic information have been constructed. In each nucleus, the 4^+ member of the ground band is populated by two de-excitation branches of roughly equal intensity, one involving even-spin positive parity states and the other a 5^-, 7^-, 9^- ... level sequence. In Fig 1, the ^{192}Pt level scheme is shown. Most remarkable are the energy spacings in the positive parity yrast sequence, which has the appearance of a highly exaggerated back-bending type structure. In ^{190}Pt, the positive parity sequence is rather similar, although the 12^+-10^+ and 10^+-8^+ spacings are not as drastically reduced. While the energy spacing suggests that intrinsic excitations such as $(h_{11/2}\pi)^{-2}$ and $(i_{13/2}\nu)^{-2}$ might contribute to the compositions of the 10^+ and 12^+ states, nevertheless the measured life-times of the 12^+ states show that the $12^+\rightarrow10^+$ E2 transitions are enhanced.

On the negative parity side, the most important new result is the discovery of 10^- isomers ($t_{1/2}$= 230 ns in ^{192}Pt, $t_{1/2}$=47 ns in ^{190}Pt), which play a major role in the de-excitation cascades. A pretty good case can be made for interpreting these as shape isomers analogous to the known 9/2[505]ν, 11/2[615]ν 10^- isomer in ^{190}Os, although this is at present a tentative conclusion.

The results for ^{188}Pt differ markedly from those for ^{190}Pt and ^{192}Pt in that the 10^+ member of the ^{188}Pt ground band is not populated by any strong de-excitation branch, and no isomeric 10^- state is in evidence in this nucleus. On the other hand, the negative parity E2 cascades are well developed up to higher spin values than in the heavier Pt nuclei.

Digestion of these results and consideration of their implications is continuing.

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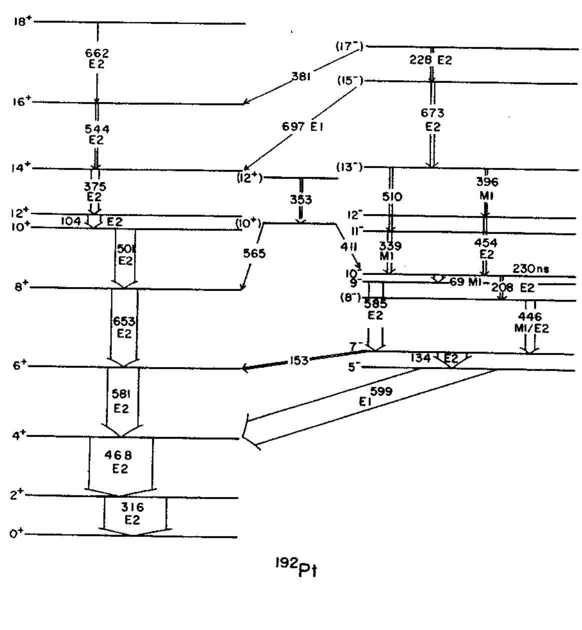

^{192}Pt