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Decay of Re^{184} Isomers and the Level Scheme in W^{184}

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The decay properties of a rhenium activity followed for over five years have led to its assignment to Re^{184} with isomeric states of 33±3 and 169±8 days. An unidentified rhenium species with a half-life ≥21 years is also present in very small abundance. Energies (and intensities) of the gamma rays determined from the single-crystal and coincidence studies are 0.059(146), 0.111(27.3), 0.163(1.8), 0.217(4.4), 0.253(7.0), 0.318(1.7), 0.384(1.2), 0.539(0.9), 0.540(0.8), 0.641(3.3), 0.770(1.5), 0.793(64.6), 0.894(25.2), 0.904(71.7), 0.909(3.1), 0.97(0.8), 1.03(1.1), 1.04(0.05), 1.16(0.5), and 1.28(0.2) MeV. Gamma coincidence spectra were measured by gating on every gamma-ray peak in the single-crystal spectrum. The 163-keV gamma ray and most of the intensity of the peak at 217 keV appear to be associated with levels in Re^{184}, where the latter energy represents the isomeric transition from the 169-day state.

Levels (and spins) in W^{184} are proposed at 0.111(2+), 0.364(4+), 0.748(6+), 1.287(8+), all members of the ground-state rotational band; 0.904(2+), 1.005(3+), 1.134(4+), members of the γ-vibrational band; 1.222, 1.273, 1.33, and 1.40 MeV. Re^{184} levels are assigned at 0.163 and 0.217 MeV.

The difference between the experimental and theoretical reduced transition probability ratios from the γ-vibrational to the ground-state rotational band are accounted for by a mixing of the two bands.

I. INTRODUCTION

IN 1956 when the present work was started, the literature contained only a sparse amount of information on Re^{184}, and this was primarily concerned with production of the activity and half-life measurements of its decay. Most of these early half-life determinations gave values of from 50 to 54 days.[1-4] A somewhat shorter Re decay period was reported by Lindner,[5] however. He irradiated Re with neutrons and observed half-lives of 40 and 150 days and about 5 years. The 40-day period was assigned to Re^{184} and he concluded that one of the two longer lived fractions must be due to Re^{189}.

Wilkinson and Hicks[3] had examined the conversion electron spectrum of a 50-day rhenium activity and reported transitions at 43, 159, 205, and 285 keV. Wilkinson[3] in another report had listed electron lines for transitions of 159, 206, 244, 784, and 890 keV. Turner and Morgan[4] made absorption measurements on the radiations from a 50-day rhenium activity and reported 0.1-, 0.20-, and 0.70-MeV electrons and a 1.0-MeV gamma ray.

There was an apparent need for a more detailed study of the decay properties of Re^{184}. A knowledge of the energy levels in the daughter nucleus W^{184}, including the branching ratios of the gamma rays between these levels, is pertinent to collective model interpretations. It is found that as the nuclei move out of the region of stable spheroidal deformation, there is an increased "softening" of the nuclear potential toward shape vibrations, as indicated by the reduced moment of inertia of the ground-state band and an increased vibrational-rotational interaction. In the present work an attempt has been made not only to characterize the energies of these excited levels in W^{184}, but also to establish the intensities of the gamma-ray transitions from them in an effort to learn more about how the nuclear properties are affected as the nuclei begin to emerge from the region of strong deformation.

During the course of this work,[6] Gallagher, Strominger, and Unik[7] and Harmatz, Handley, and Mihelich[8] reported Re^{184} decay schemes containing a number of dissimilar features. The decay scheme proposed in the current study has features in common with and some in disagreement with each of the two preceding papers.

Recently, Bodenstedt *et al.*[9] have measured the half-life of Re^{184} as 38±1 days and have performed angular correlation measurements on the gamma-ray depopulation of the two lowest vibrational states in W^{184}. Numerous other investigators[10-17] have examined the

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properties of some of the low-lying W^{184} levels following Coulomb excitation.

II. SOURCE PREPARATION AND HALF-LIFE DETERMINATION

There were three sources of Re^{184} used in these experiments. For the first one, $KReO_4$ was irradiated in the Oak Ridge LITR for three weeks and Re^{184} was produced by the reaction $Re^{185}(n,2n)Re^{184}$. The source was then set aside for several weeks to allow the 91-h Re^{186} to decay, and afterwards was dissolved in a weakly basic solution. Next, WO_3 was added and the solution was made acid with HCl resulting in the precipitation of H_2WO_4. This was done in order to remove any tungsten activity which might have been present. The rhenium was then precipitated as Re_2S_7 by the addition of H_2S and the precipitate was dissolved in a mixture of NaOH and H_2O_2, followed by a ferric hydroxide scavenging. At this point Re_2S_7 was once again precipitated; a source was mounted; and its gamma-ray spectrum was taken with a 3-in.×3-in. NaI crystal spectrometer.

As a further check on the presence of radioactive impurities, considerable additional purification of the sample was then undertaken. The Re_2S_7 was dissolved in NaOH-H_2O_2 and passed through a cation exchange column of Dowex-50. The column was checked afterwards and it showed no residual activity. This solution was next made acid with HCl and tetraphenyl arsonium chloride was added in order to precipitate the rhenium. The tetraphenyl arsonium perrhenate was dissolved in ethyl alcohol, and this solution was passed through a Dowex-2 anion exchange column. Rhenium was then removed from the column by eluting with 2*M* $HClO_4$. Finally, Re_2S_7 was precipitated, and once again its gamma-ray spectrum was taken. There appeared to be no change between this spectrum and the one which was observed before the ion exchange separations were done.

The second source of Re^{184} used in these studies was prepared from a sample enriched to 85% in Re^{185}. This source was shielded in 1/5-in. cadmium in order to reduce the number of (n,γ) reactions producing Re^{186}. It was irradiated in the LITR for five days, and was also set aside for several weeks to allow the short-lived activities to decay. Since the extensive chemistry performed on the previously described source appeared to make no appreciable difference in the shape of the gamma spectrum, it was concluded that in this case, the only chemistry necessary would be a series of precipitation steps.

A third irradiation of ordinary $KReO_4$ was made for seven days in the Oak Ridge Research Reactor. The chemistry consisted of a series of sulfide precipitations and a terminal step in which the activity was precipitated as tetraphenyl arsonium perrhenate.

After about four years a final check was made on the purity of the first of these three sources. The rhenium in it was distilled from H_2SO_4 and no detectable change was observed in the gamma-ray spectrum of the activity before and after this distillation.

The decay of the activity produced from each of the three neutron irradiations was followed with an end-window proportional counter and one of the decay curves taken in this manner is shown in Fig. 1. Computer least-squares fits were made for two samples whose decay had been followed for more than five years and from these, average values of 33±3 days, 168±8 days, and ≥ 21 years were determined for the three components present. These are the values shown in Fig. 1. The errors quoted are conservative estimates of both the statistical and systematic errors.

It should be pointed out that the decay curve for a

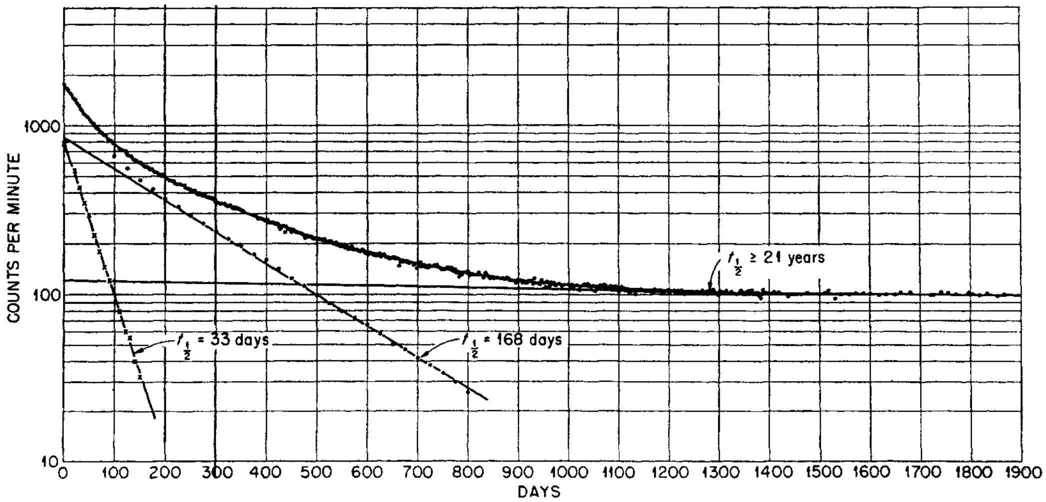

FIG. 1. Decay curve of Re^{184} taken with an end-window proportional counter. The ≥ 21 year component is from an unidentified rhenium activity.

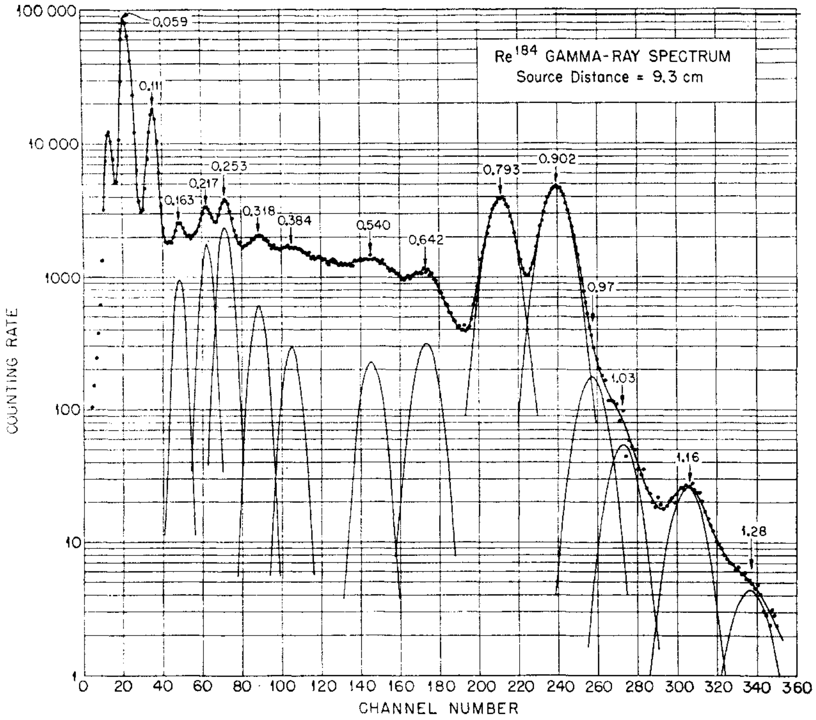

FIG. 2. Single-crystal gamma-ray spectrum of Re^{184}. The region above channel 250 was normalized to a spectrum taken at reduced gain.

rhenium source which had undergone the extensive ion-exchange purification steps described above and the curve for a source which had not are very similar. Thus, the indications are that the three periods observed must be due to rhenium activity.

Gamma-ray spectra were also measured periodically for all sources. The decay of each prominent full-energy peak gave a simple two-component curve with half-lives of about 33 and 170 days, in good agreement with the two shorter lived periods observed with the end-window proportional counter. From this information and that known[18] about the other Re isotopes it is therefore concluded that there are two isomers of Re^{184} with half-lives of 33±3 and 169±8 days.

The fact that the ≥ 21 year period was not observed in the decay of any of the prominent gamma rays and yet appears quite markedly in Fig. 1 probably indicates further that it is due to the presence of a minute trace of some rhenium activity which decays by emission of beta rays. Re^{184} decays almost totally by electron capture thus accounting for its lower counting efficiency on the beta proportional counter.

Re^{184} half-lives of 33 and 169 days are in disagreement with all previously reported results. However, since most of these workers were using Re^{184} sources which contained appreciable 71-day Re^{183} (there were no indications for such in the present work), it is not difficult to see how an apparent value of about 50 days might be found. This is especially true if the decay were followed for a period of at most a few months.

III. SINGLE-CRYSTAL SPECTROMETRY

The gamma-ray spectra were measured with 3-in. ×3-in. cylindrical NaI crystals mounted on DuMont 6363 photomultiplier tubes. Pulse-height analysis was performed by using a 20-channel analyzer in the early experiments and a 256-channel analyzer in the later ones. The spectrum of a 112-day-old Re^{184} sample is shown in Fig. 2. Decomposition of this spectrum was done by using Gaussian shapes of appropriate widths for the full-energy peaks and by matching the Compton distributions with those of standards run under similar experimental conditions. The region above channel 250 was normalized to a spectrum taken at reduced gain. The spectral analysis shows that in the high-energy region, there are gamma rays at 0.97, 1.03, 1.16, and 1.28 MeV; but part of the distribution is still unexplained, indicating that other weak transitions quite probably occur in this energy range. The coincidence data show that the peak at 1.03 MeV and also several of the lower energy peaks are complex and involve multiple gamma-ray transitions close to the indicated energy. A study of the portion of the spectrum below 90 keV with an argon proportional counter revealed only the expected x rays.

To reduce the effects from large-angle scattering, a single-crystal spectrum was measured with the radiations collimated through a $\frac{1}{4}$-in.-diam hole in a 2-in. thick antiscattering lead barrier. The results show

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[18] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington 25, D. C.).

TABLE I. Summary of Re^{184} gamma-ray data.

E_γ (MeV)	Singles intensity[b]	"Coincidence quotient"[a] with gamma-rays of energy (Mev):					
		0.059	0.111	0.217[c]	0.253	0.318	0.384[c]
0.059±0.003	146 ±15	0.19 ±0.03	0.49 ±0.04	0.39 ±0.05	0.88 ±0.10	0.24 ±0.10	0.75 ±0.25
0.111±0.001	27.3 ± 3.3	0.090 ±0.008		0.048±0.015	0.39 ±0.05	0.15 ±0.07	0.22 ±0.10
0.163±0.003	1.8 ± 0.5	0.0064±0.0015					
0.186±0.004						0.0021±0.0016	
0.217±0.003[c]	4.4 ± 1.2	0.011 ±0.003	0.014 ±0.005		0.026±0.012	0.021 ±0.015	
0.253±0.003	7.0 ± 1.0	0.023 ±0.003	0.070 ±0.008	0.014±0.006	0.017±0.011	0.031 ±0.025	0.74 ±0.10
0.318±0.003	1.7 ± 0.6	0.0027±0.0018	0.012 ±0.003		0.010±0.009	0.009 ±0.007	0.039±0.020
0.384±0.005[c]	1.3 ± 0.7	0.0045±0.0020	0.016 ±0.004		0.16 ±0.02	0.013 ±0.009	0.013±0.010
0.539±0.005[c]	1.7 ± 0.9	0.0057±0.0025	0.018 ±0.005		0.21 ±0.02	0.018 ±0.005	0.66 ±0.09
0.641±0.007	3.3 ± 1.4	0.011 ±0.004	0.020 ±0.006	0.016±0.008	0.37 ±0.04	0.031 ±0.009	0.04 ±0.04
0.770±0.006	66.1 ± 7.0			0.025±0.009[f]	0.18 ±0.03		
0.793±0.005		0.30 ±0.03	0.46 ±0.05[d]			0.45 ±0.05	0.05 ±0.05
0.894±0.006	100	0.37 ±0.04	0.20 ±0.02[d]	0.21 ±0.03			0.04 ±0.04
0.904±0.006						0.45 ±0.05	
0.909±0.007			e		0.44 ±0.05		
0.97 ±0.03	0.8 ± 0.5	0.0073±0.0040	0.0066±0.0035		0.012±0.005		
1.03 ±0.02[c]	1.2 ± 0.6	0.0078±0.0020	0.0093±0.0030		0.006±0.002		
1.16 ±0.03	0.9 ± 0.4	0.0014±0.0008	0.0051±0.0020				
1.28 ±0.05	≤0.15	0.0006±0.0005	0.0016±0.0012				

E_γ (MeV)	Singles intensity[b]	"Coincidence quotient"[a] with gamma-rays of energy (MeV):					
		0.539[c]	0.641	0.793[c]	0.902[c]	1.03[c]	1.16
0.059±0.003	146 ±15	0.13 ±0.11	0.80 ±0.30	0.93 ±0.10	0.64 ±0.05	0.46 ±0.15	0.20±0.09
0.111±0.001	27.3 ± 3.3	0.12 ±0.11	0.19 ±0.06	0.27 ±0.05[d]	0.073 ±0.007[d]	0.078±0.025	0.14±0.08
0.163±0.003	1.8 ± 0.5						
0.186±0.004				0.007 ±0.004	0.0011±0.0008		
0.217±0.003[c]	4.4 ± 1.2		0.068±0.025	0.0046±0.0016	0.0094±0.0015		
0.253±0.003	7.0 ± 1.0	0.70 ±0.10	0.77 ±0.12	0.018 ±0.003	0.013 ±0.002	0.046±0.025	
0.318±0.003	1.7 ± 0.6	0.025±0.015	0.029±0.010	0.016 ±0.003	0.0088±0.0015		
0.384±0.005[c]	1.3 ± 0.7	0.48 ±0.07	0.02 ±0.02	0.003 ±0.003	0.002 ±0.002		
0.539±0.005[c]	1.7 ± 0.9	0.05 ±0.05					
0.641±0.007	3.3 ± 1.4	0.03 ±0.03					
0.770±0.006	66.1 ± 7.0						
0.793±0.005							
0.894±0.006	100						
0.904±0.006							
0.909±0.007							
0.97 ±0.03	0.8 ± 0.5						
1.03 ±0.02[c]	1.2 ± 0.6						
1.16 ±0.03	0.9 ± 0.4						
1.28 ±0.05	≤0.15						

[a] If there is no number shown for the "coincidence quotient," it can mean either that there was no evidence for a coincident peak or that there was possibly a small indication for it, but the nature of the data made its inclusion in the table questionable.

[b] Relative to the multiple gamma rays at 0.902 MeV in Fig. 1 as 100 units. The intensities shown here are those obtained from the single-crystal experiments, whereas the intensities shown in the decay scheme are the best values as determined from both the single-crystal and coincidence data. These single-crystal intensities are for a Re^{184} source 112 days after irradiation; the coincidence values are for sources whose ages ranged up to 146 days. However, these data have not been corrected to the same time since only minor changes are necessary and these are well within the experimental errors on the numbers.

[c] There is evidence for the presence of multiple gamma rays with about this energy.

[d] This value has been corrected for angular correlation effects. $\overline{W}(180°)$ based on the results of Bodenstedt *et al.* (reference 9) is 1.10 for the 793–111-keV gamma-ray cascade and 0.82 for the 894–111-keV cascade. However, since solid sources were used in the present work, and as we do not know their crystal field effects which tend to suppress the correlation, average values $\overline{W}(180°)=1.05$ and 0.91 were used for the two respective cases. Although when gating on 111 keV, approximately 2% of the intensity of the 793-keV coincident peak was from a 770-keV gamma ray, the angular correlation correction was applied as if it were a single component. Likewise, the coincident peak at 894 keV was corrected as if it were from this gamma ray alone, although a 909-keV gamma ray comprises about 10% of its intensity.

[e] This gamma ray is also in coincidence with 111 keV, but no effort has been made to resolve it from the intense 0.894-MeV peak present.

[f] The energy of the coincidence peak is 0.787 MeV. See text for discussion of its possible nature.

quite clearly that the 163-keV peak cannot be accounted for by scattering.

Energies of the more intense gamma-ray peaks were determined by simultaneous measurements of Re^{184} with standard sources of Co^{60}, Cs^{137}, Na^{22}, and Cr^{51}. The energy of the 0.111-MeV peak of Re^{184} had already been accurately established,[10] so it and the other prominent Re^{184} peaks served as internal energy standards for further experiments.

In Column 1 of Table I are listed the best gamma-ray energy values as determined from both single-crystal and coincidence experiments. Column 2 shows the single-crystal intensities (corrected for summing) relative to the combined peaks at 0.902 MeV in Fig. 2 as 100 units. All of the data of Table I have been corrected for gamma-ray losses due to absorption in the crystal housing and due to escape of iodine x rays from the crystal, but they have not been corrected for internal conversion. These relative intensities, which are for the 112-day-old source of Fig. 2, will show some small changes with time as a result of W^{184} level population by two isomeric states of Re^{184}.

For each Re^{184} source prepared in these experiments, gamma-ray spectra have been taken at given time intervals, which in the case of one sample has covered a period of about six years. These measurements were always started as soon as the 91-h Re^{186} had decayed to a negligible level (about 70–80 days after the sample was removed from the reactor). A plot of the decay of individual gamma-ray peaks shows that at the time of the first measurement, the disintegration rate of the 33-day component, for all except the 163-keV gamma ray, was greater than the 169-day component by factors ranging as high as twenty. However, the 163-keV gamma ray appeared to decay with a simple half-life of about 170 days. The 318- and the 217-keV gamma rays showed roughly equal amounts of the two decay periods at the time of the first count.

In the preceding section, it was pointed out that after four years, the first Re^{184} source was further purified by distillation of the rhenium. Before doing this, a peak at 139 keV had become detectable in the gamma-ray spectrum. Since the distillation produced no effect on the relationship of this peak to the rest of the spectrum, it is concluded that the gamma ray is due to a very long-lived rhenium activity. Accurate measurements of the decay rate of this gamma ray have not been possible, however. There are also some slight indications for higher energy gamma rays associated with this long decay period.

IV. GAMMA-GAMMA COINCIDENCE SPECTRA

For the gamma-gamma coincidence measurements, the source was placed at the center of a collimating anti-Compton shield and was viewed by two 3-in.×3-in. NaI crystals at 180° to each other. A "fast-slow" coincidence circuit having a resolving time, 2τ, of 0.19 μsec was used to gate the multichannel analyzer. After correcting each spectrum for the "chance" coincidence contribution, the spectral analysis was performed in the same manner as described for the single-crystal data.

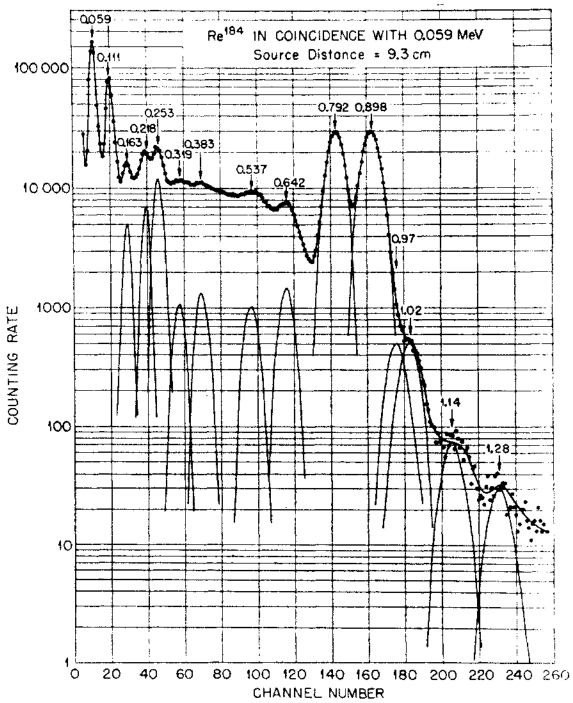

FIG. 3. Re^{184} gamma-ray spectrum in coincidence with an 8-keV window set at 0.059 MeV.

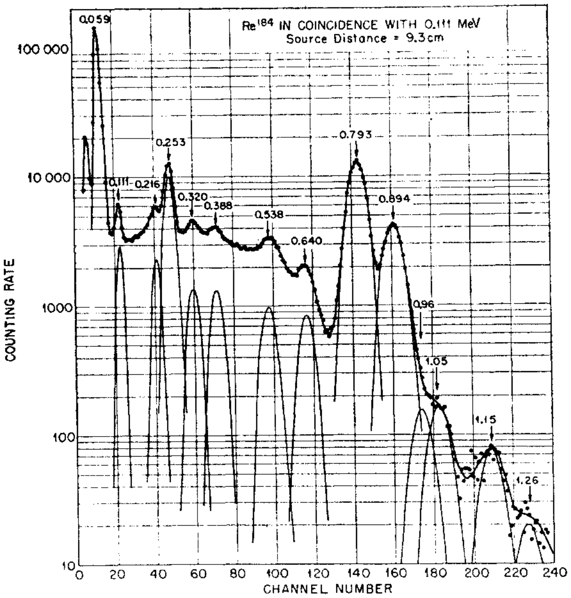

FIG. 4. Re^{184} gamma-ray spectrum in coincidence with a 12-keV window set at 0.111 MeV.

Coincidence data are conveniently discussed in terms of "coincidence quotients," q, the ratio of the number of

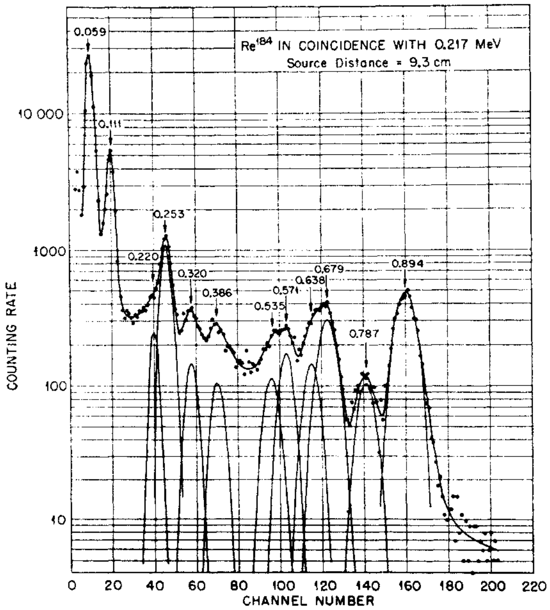

FIG. 5. Gamma rays from Re^{184} in coincidence with 0.217 MeV. The single-channel window was 20 keV wide.

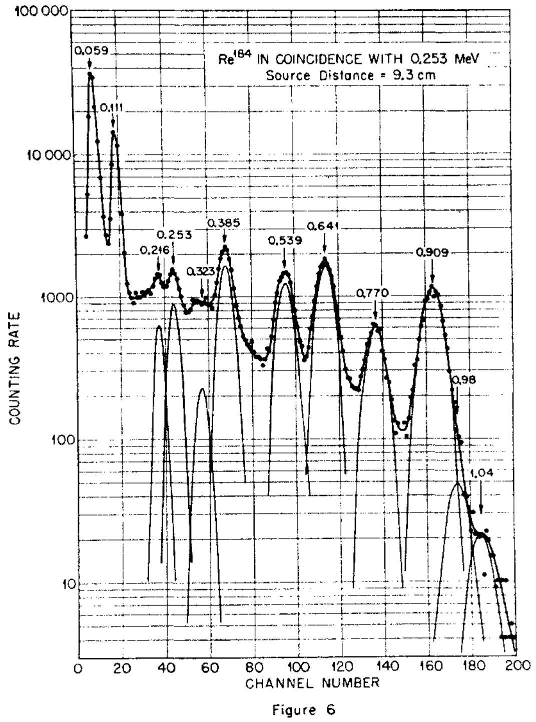

FIG. 6. Gamma rays from Re^{184} in coincidence with 0.253 MeV. The single-channel window was 17 keV wide.

coincident gamma rays of interest to the number of "gating" gamma rays in the single-channel window. The coincidence quotients for most of the gamma-gamma coincidence experiments are shown in Table I. These q values are used in conjunction with the single-crystal intensities and the decay scheme of Fig. 13 to calculate the intensity of each gamma-ray transition. This procedure usually involves a series of successive approximations until internal consistency is achieved.

Often a gamma-ray peak may appear prominent in a coincidence spectrum and yet in the summary of gamma-gamma coincidence information in Table I the coincidence quotient may seem strikingly small and in some cases not be listed at all. This is a result of removing the coincidence contribution from higher energy gamma rays which have Compton events falling in the single-channel window. The details of the method used for calculating these coincidence quotients has been discussed previously.[19]

Just as with the single-crystal experiments, the coincidence measurements were repeated at different times in order to study further the change in population of W^{184} levels. All except two of the coincidence spectra shown in the figures were taken between 110 and 146 days after a source was removed from the reactor. The spectra in coincidence with 0.793 and 0.902 MeV in Figs. 11 and 12, respectively, are shown to illustrate this marked change in coincidence intensities with time.

Figure 3 gives the spectrum in coincidence with an 8-keV single-channel window centered at 59 keV. The main difference between this spectrum and the single-crystal data of Fig. 2 is in the intensity of the 59-keV gamma ray.

The spectrum in coincidence with events in a 12-keV wide window centered on the 0.111-MeV peak is shown in Fig. 4. These results indicate clearly that the 0.902-MeV peak in the single-crystal spectrum is complex. Further, from the data of Fig. 4, it is possible to assign both an energy and an intensity to the 0.894-MeV component cascading via the 0.111-MeV gamma ray.

When the single-channel analyzer was set on the 163-keV peak, scattering events in the window could account for the observed coincidence spectrum within the estimated errors.

In Fig. 5 is shown the spectrum in coincidence with a 20-keV window centered on the 217-keV peak. The principal feature indicated by this spectrum is a strong coincidence relationship between the 217- and the 894-keV gamma rays. There are also a number of troublesome aspects about the data of Fig. 5. On the high-energy side of the 0.894-MeV peak is an undefined distribution of low intensity. There are peaks at 0.571 and 0.679 MeV which are the result of large-angle scattering from the face of one detector back to the other. When the two detectors are at 180° to each other (the experiment was limited to this single arrangement) and the single-channel window is set in the vicinity of the backscatter peak, such spurious coincidence peaks are

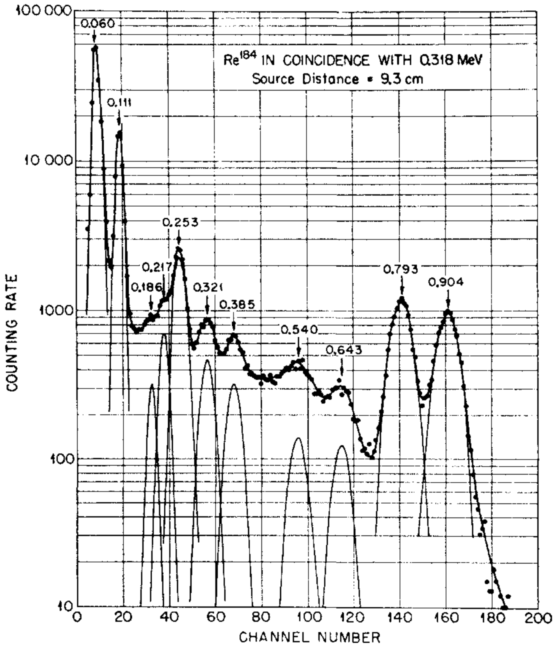

FIG. 7. Gamma-ray spectrum from Re^{184} coincident with the events in a 29-keV window set at 0.318 MeV.

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[19] N. R. Johnson, E. Eichler, G. D. O'Kelley, J. W. Chase, and J. T. Wasson, Phys. Rev. 122, 1546 (1961).

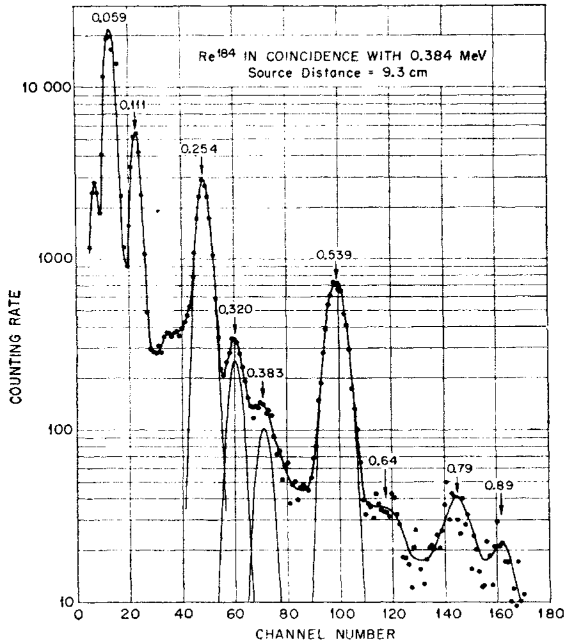

FIG. 8. Re^{184} gamma-ray spectrum in coincidence with a 33-keV window centered at 0.384 MeV.

to be expected. Here the 0.571- and 0.679-MeV peaks are accounted for by coincidence scattering events from the gamma rays at 0.793 and those centered at 0.902 MeV, respectively, in the single-crystal spectrum. About one-third of the intensity of the peak at 0.787 MeV in Fig. 5 can be accounted for by Compton-scattered events from gamma rays in coincidence with the 0.770- and 0.793-MeV transitions. Although done with considerable uncertainty, the remaining intensity is assigned in Table I to true coincidences between the 217-keV gamma ray and the 770- and 793-keV peaks.

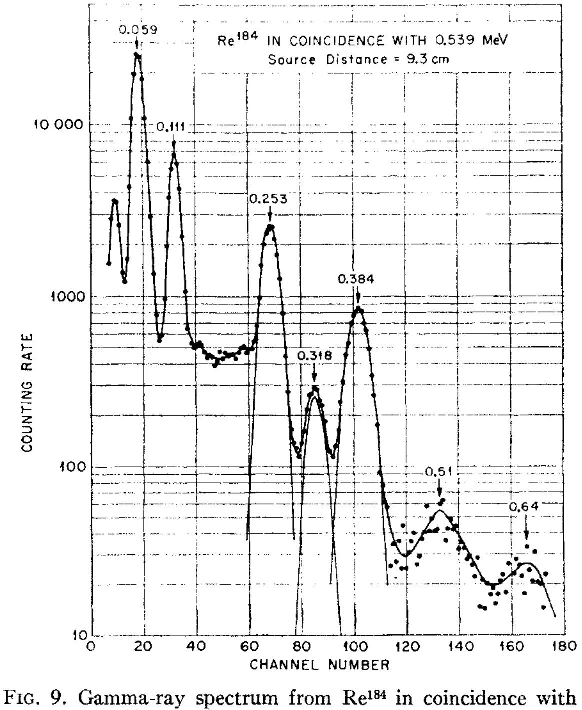

FIG. 9. Gamma-ray spectrum from Re^{184} in coincidence with a 40-keV window centered at 0.539 MeV.

When a 17-keV single-channel window gated on the 0.253-MeV peak, the spectrum of Fig. 6 was obtained. This spectrum provides the best details on some of the very low-intensity gamma rays. For example, when this experiment had been repeated many times, the energies 770±6 and 909±7 keV were considered reliable values for two of the peaks indicating two new gamma rays which were masked in all other measurements. Figure 6 also gives the best resolution of the 641-keV peak.

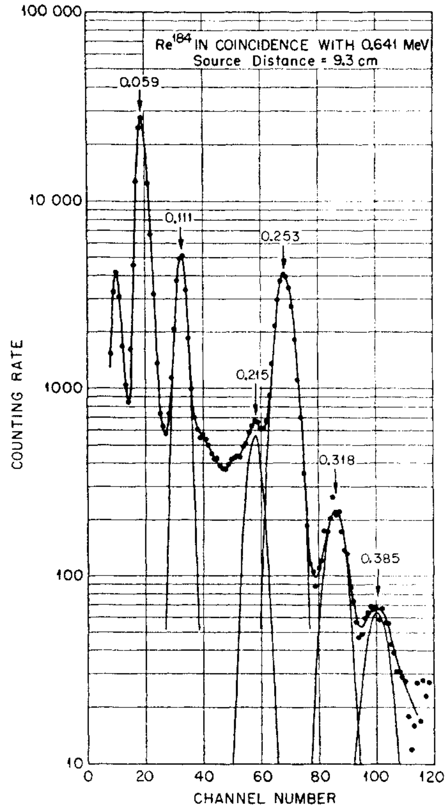

FIG. 10. Gamma rays from Re^{184} in coincidence with 0.641 MeV. The single-channel window was 44 keV wide.

The spectrum in coincidence with 318 keV is shown in Fig. 7. It serves as a means for accurately establishing the energies and relative intensities of the 0.793- and 0.904-MeV transitions originating at the 0.904-MeV level in W^{184}. Most of the low-energy portion of this spectrum results from coincidences with Compton events in the single-channel window. As a result, several of the q values in Column 7 of Table I carry nearly 100% limits of error. In many of these cases, it is very doubtful that there is a real coincidence between the 317-keV transition and the designated gamma ray.

In Figs. 8 and 9 are shown the spectra coincident with 0.384 and 0.539 MeV, respectively. These two spectra point out quite clearly the strong coincidence relationship between the 0.253-, 0.384-, and 0.539-MeV gamma rays. In both spectra, there is left after analysis a small residual distribution between the 0.111- and 0.253-MeV peaks. This residue is poorly defined, but it appears to be about the intensity necessary to account for Compton scattered events in the window. In Fig. 8 there is considerable question about the coincidence peaks at 0.64, 0.79, and 0.89 MeV. These may be due to very weak real coincidences, although the unusual scattering phenomena observed when the two detectors are at 180° may well account for much of the intensity. A similar statement also applies for the 0.51- and 0.64-MeV peaks in Fig. 9 and for the 385-keV peak in the spectrum coincident with 0.641 MeV shown in Fig. 10.

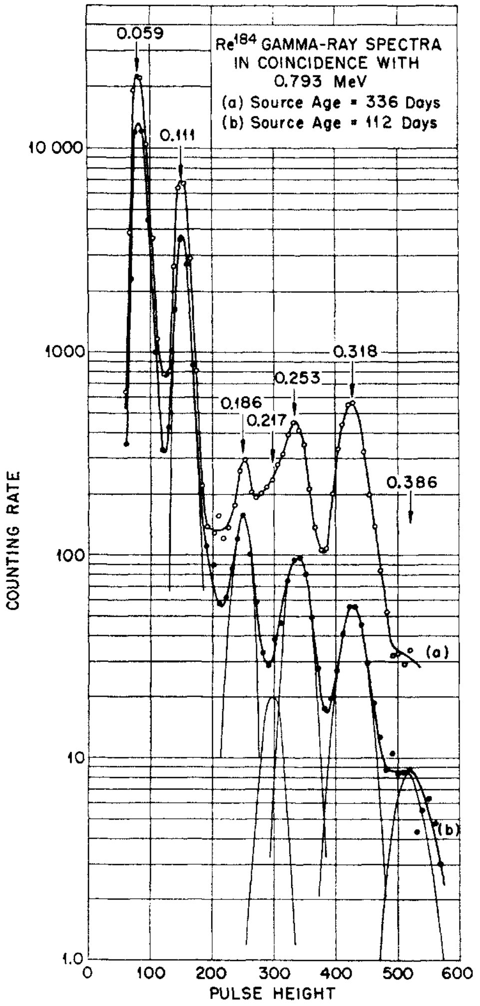

FIG. 11. Re^{184} gamma-ray spectrum in coincidence with a 45-keV single-channel window set at 0.793 MeV. Curve (a) is for a source age of 336 days and curve (b) is for a source 112 days after irradiation. These two spectra are shown to demonstrate that there is direct population of W^{184} levels by both isomeric states of Re^{184}.

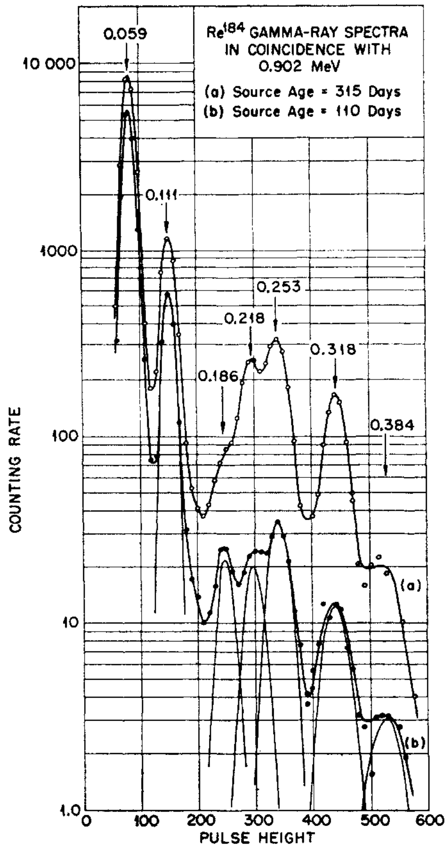

FIG. 12. Re^{184} gamma-ray spectra in coincidence with a 65-keV window set at 0.902 MeV. Curve (a) is for a source 315 days old and curve (b) is for one 110 days old. These two spectra demonstrate that there is direct population of W^{184} levels by both isomeric states of Re^{184}.

In this latter spectrum, most of the distribution between the 0.111- and 0.215-MeV peaks is likewise the result of scattering.

Figures 11 and 12 show the spectra coincident with the single-channel window set at respective positions of 793 and 902 keV. In each case, two spectra are shown to illustrate how the coincidence intensities varied with the age of the Re^{184} source. Both figures indicate peaks at about 186 and 385 keV. How these two gamma rays are related to the decay of Re^{184} is not understood but it is possible that at least partially they may be due to large-angle scattering. The spectra obtained with the single-channel window set on the 1.03- and 1.15-MeV peaks are not shown, but the *q* values obtained in each case are given in Table I.

V. DECAY SCHEME

A decay scheme of Re^{184} is shown in Fig. 13. It is based primarily on the data in Table I which was accumulated for a source between 110 and 146 days after it was removed from the reactor. Thus, the relative intensities on each gamma-ray branch may be assumed to be representative of a Re^{184} source about 130 days old.

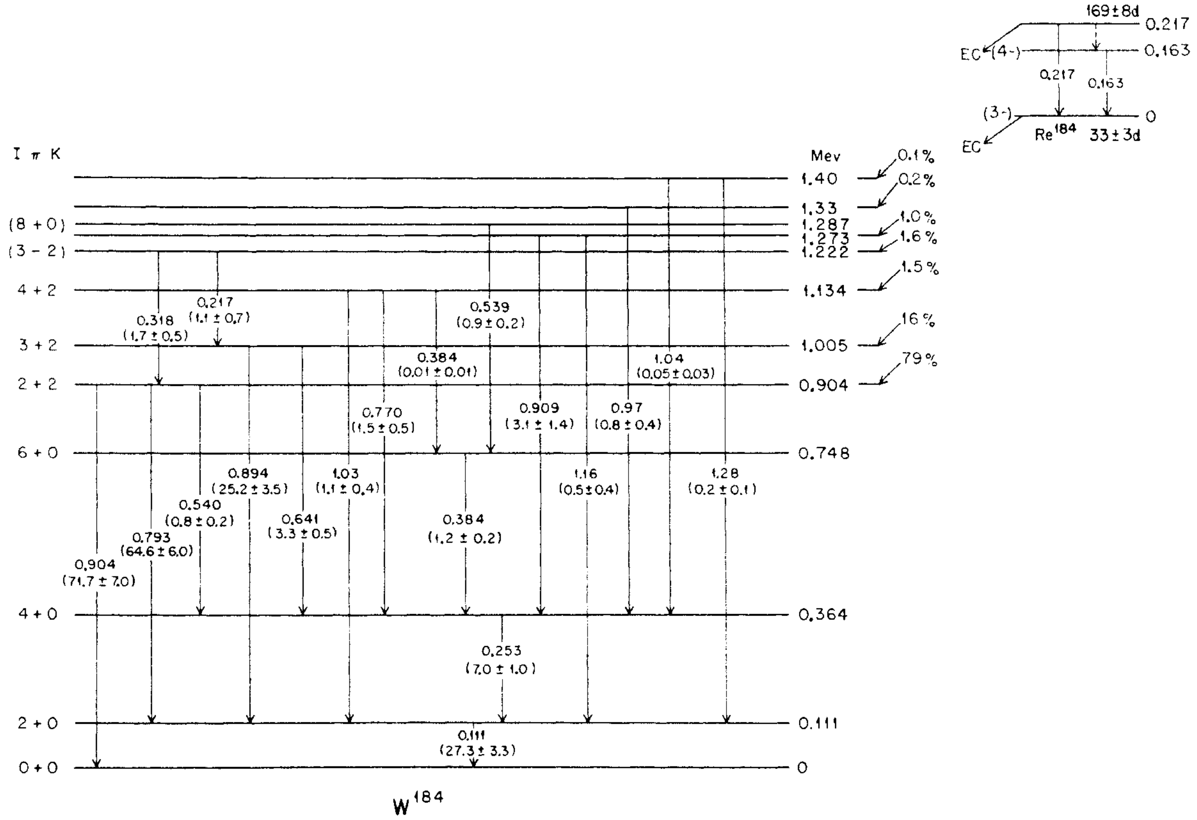

FIG. 13. Decay scheme proposed for Re^{184}. Relative gamma-ray intensities deduced from the single-crystal and coincidence data are given in parentheses beneath the gamma-ray energies. Intensities of the electron-capture branches were calculated from the relative gamma-ray intensities shown in the decay scheme.

All of the data accumulated from three different Re^{184} sources are in general agreement with this scheme. Many of the arguments which led to the formulation of Fig. 13 are rather involved and all of them will not be covered in detail here.

As indicated earlier, the first excited level in W^{184} at 111 keV has been studied by numerous investigators.[7–17] In Fig. 13, the 27.3 units of intensity assigned for the transition from this level is the value found from the single-crystal data. This value is in good agreement with that (27.6 units) determined from coincidence experiments.

The second excited level is assigned at 364 keV, also in agreement with other reports.[7,8,9,13] Both the single-crystal results and the spectrum in coincidence with the 111-keV gamma ray indicated that the photon intensity of the transition de-exciting this level is 7.0 units.

In particular, the spectra in coincidence with 0.253, 0.384, and 0.539 MeV require additional W^{184} levels at 0.748 and 1.287 MeV. These two levels, along with those at 364 and 111 keV are assigned as members of the ground-state rotational band having $K=0$ and spins of 0+, 2+, 4+, 6+, and 8+. This assignment is based on the observed energy spacings, which agree closely with those expected for such a rotational sequence, and on the way in which each level is de-excited. There is some question about this latter point in the case of the 8+ member of the band at 1.287 MeV. The spectra in coincidence with 0.793 and 0.902 MeV indicate the slight possibility of a very weak 385-keV gamma ray cascading into the 904-keV level. If this transition exists and if it originates from the 1.287-MeV level, then the 8+ assignment is in error (the spin of the 904-keV state is well established as 2+[7–9,16,17]). The possibility of a 385-keV gamma ray here seems extremely remote, however, as one would expect to see other transitions from the 1.287-MeV level to the nearby states of spins intermediate between 2+ and 6+, and these are not observed. Of course, there might be a second level very close to 1.287 MeV (perhaps a member of a $K=2$- band) which could account for such a low-intensity transition.

The energy of the level at 904 keV is based on the coincidence spectrum obtained by gating on 318 keV, and in turn, this result also establishes a level at 1.222 MeV. The approximate position of this state is given by several other coincidence experiments, but it is only when the single-channel window is set on the 318-keV peak that the 904- and 793-keV gamma rays are well resolved from all other transitions with similar energies. This is the same energy for this level as found by Gallagher *et al.*[7] and Harmatz *et al.*[8]

Observation of an 894-keV gamma ray in coincidence

TABLE II. Reduced transition probability ratios for deexcitation of γ-vibrational levels of W^{184}.

Initial state		Final states			Reduced transition probability ratios			
$K, I\pi$	keV	$K, I\pi$	$K, I\pi$	$K, I\pi$	This work	Theoretical[a]	Gallagher *et al.*[b]	Harmatz *et al.*[c]
2, 2+	904	0, 0+	0, 2+	0, 4+	0.57/1/0.085	0.70/1/0.050	0.58/1/0.05	0.53/1/0.04
2, 3+	1005		0, 2+	0, 4+	1.43/1	2.50/1	3.6/1	1.42/1
2, 4+	1134	0, 2+	0, 4+	0, 6+	0.17/1/0.2	0.34/1/0.09	d	0.16/1/?[e]

[a] The theoretical relation is given by the square of the ratio of Clebsch-Gordon coefficients; see, for example, A. H. Wapstra, G. J. Nijgh, and R. Van Lieshout, *Nuclear Spectroscopy Tables* (North-Holland Publishing Company, Amsterdam, 1959).
[b] C. J Gallagher, D. Strominger, and J. P. Unik, Phys. Rev. **110**, 725 (1958).
[c] B. Harmatz, T. H. Handley, and J. W. Mihelich, Phys. Rev. **123**, 1758 (1961).
[d] C. J. Gallagher *et al.* did not report a level at 1134 keV.
[e] B. Harmatz *et al.* did not report a $K=0$, $I=6+$ level.

with 111 keV and a 641-keV peak in coincidence with 253 keV establishes the level at 1.005 MeV. Similarly, the level at 1.134 MeV is required by the coincidence information in Table I.

From the work of Bohr and Mottelson[20] on the collective nuclear model it is now established that many excited levels in deformed nuclei are vibrational in nature. The lowest order shape vibrations are quadrupole vibrations which separate into two modes, a β vibration with zero component of vibrational angular momentum around the symmetry axis ($\nu=0$) and a γ vibration with a corresponding component $\nu=2$. (In the region of Th and U the observed octupole vibrational states are generally lower in energy than the quadrupole states.)

According to the collective model, the ways in which such collective excitations should decay to the members of the ground-state rotational band are predictable.[21,22] If there is no mixing between the rotational bands, the ratio of the reduced transition probabilities for emission of a given multipole radiation $B(L)$ from state i to different members f, $f'\cdots$ of a rotational family is simply given by the ratio of the squares of vector addition coefficients,[21,22]

$$\frac{B(L,I_i\rightarrow I_f)}{B(L,I_i\rightarrow I_{f'})}=\frac{\langle I_iLK_iK_f-K_i|I_iLI_fK_f\rangle^2}{\langle I_iLK_iK_{f'}-K_i|I_iLI_{f'}K_f\rangle^2}, \quad (1)$$

where L is the multipolarity of the transition, I is the total angular momentum of the indicated state, and K is the projection of the total angular momentum vector on the nuclear symmetry axis. In the case of the lowest member of a γ-vibrational band ($K=2, I=2+$) the expected relative reduced transition probabilities are $7:10:\frac{1}{2}$ for the $E2$ radiation to the $I=0+$, $2+$, and $4+$ levels of the ground-state rotational band. For decay from the $2+$ member of the β-vibrational band ($K=0$), the corresponding ratio is 7:10:18. (It is known that mixing of the $K=0$ and the $K=2$ bands can cause deviations from the theoretical predictions; further attention to this aspect will be given in Sec. VI.)

In the present work, considerable effort has been made to obtain reliable gamma-ray branching ratios in order to understand the nature of these collective excitations in W^{184}. The experimental ratios found for the reduced transition probabilities from the 904-keV level are 5.7:10:0.085. This seems a rather strong indication that the level is the $I=2+$ γ vibration, which is in agreement with the angular correlation results of Bodenstedt *et al.*[9] as well as with the assignments by other investigators.[7,8,16,17] Bodenstedt *et al.*[9] also report that the 1.005-MeV level has a spin $I=3+$; that the 894-keV transition from this level is approximately pure $E2$; and that the 793-keV gamma ray de-exciting the 0.904-MeV state must have an $M1$ admixture of less than 0.5%.

The reduced transition probabilities also imply that the 1.005-MeV level is the 3+ member of this γ-vibrational band. The gamma rays de-exciting the 1.134-MeV state are of low intensity and the experimental difficulties associated with establishing these intensities require rather large limits of error. Nevertheless, it is felt that the evidence is sufficient to designate this level as a γ vibration. Harmatz, Handley, and Mihelich[8] observed two transitions from this level which they also identify as having $K=2, I=4+$. In Table II are shown the theoretical reduced transition probabilities for each of these vibrational levels, the experimental values found from this work, and the corresponding experimental values found by Gallagher *et al.*[7] and Harmatz *et al.*[8]

Enough is not known about the natures of the radiations from the other high-energy levels to make use of these ideas in assigning their quantum numbers. The depopulation of the 1.222-MeV level, however, is not inconsistent with an assignment of $K=2$, $I=3$- if the radiations from it are considered $E1$.

The level at 1.273 MeV seems clearly indicated by a 909-keV transition in coincidence with the peak at 253 keV as well as by a 1.16-MeV gamma ray in coincidence with 111 keV. Although assigned with much less certainty than the other levels, the 1.33- and 1.40-MeV states appear necessary to account for the spectra coincident with 0.111, 0.253, and 1.04 MeV.

Figure 13 shows a number of new levels as well as several gamma rays not reported in the schemes of

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[20] A. Bohr and B. R. Mottelson, Kgl. Danske Videnskab. Selskab, Matt.-Fys. Medd. **27**, No. 16 (1953).
[21] G. Alaga, K. Alder, A. Bohr, and B. R. Mottelson, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. **29**, No. 9 (1955).
[22] K. Alder, A. Bohr, T. Huus, B. R. Mottelson, and A. Winther, Rev. Mod. Phys. **28**, 432 (1956).

Harmatz *et al.*[8] and Gallagher *et al.*[7] These include the 6+ (0.748 MeV) and 8+ (1.287 MeV) members of the ground-state rotational band and the gamma-ray transitions from each, and the levels at 1.222, 1.273, 1.33, and 1.40 MeV with their associated transitions. Harmatz *et al.*[8] report possible levels at 1011 and 1106 keV with weak transitions from each to the ground and first excited states. It would be very difficult in the present work to confirm or refute this proposal, but it is quite possible that in Fig. 13, the transitions of similar energies which are shown from the coincidence measurements to depopulate other levels, do indeed correspond to those of Harmatz *et al.*[8]

Gallagher *et al.*[7] report a tentative level at 1150 keV in order to provide for the observed coincidences between 790- and 250-keV gamma rays. The coincidence data of Table I show, however, that such is due to a weak 770-keV gamma ray cascading into the 364-keV level. They also tentatively assign a level at 1230 keV to accommodate transitions of 230 and 330 keV. Presumably this level corresponds to the one assigned at 1.222 MeV in Fig. 13 and depopulated by 318- and 217-keV transitions. Further, they proposed a spin assignment of $K=2$, $I=3-$ for this level and this also appears to be the most likely assignment for the 1.222-MeV state.

From the number of gamma rays exciting and de-exciting each level of W^{184}, the percentage of each electron capture branch has been computed. These percentages are shown in the decay scheme. As the data indicate that a very high fraction of the decay from Re^{184} occurs from its ground state (presumably $I=3-$), these numbers will be affected only slightly by the age of the sample. Although the level at 1.287 MeV shows 0.9 unit of gamma-ray intensity de-exciting it and none entering, there is no electron capture designated for the state. Due to the high K forbiddenness for electron capture to this $K=0$ state, there is very little chance that it is populated directly by Re^{184} (for a discussion of the expected spins in Re^{184} see Sec. VI). It follows that the 1.287-MeV level is probably fed by a gamma transition from a W^{184} metastable state whose K value is such that electrons capture to it is permitted.

In Fig. 13, the 1.1 units of intensity assigned for the 217-keV transition going to the level at 1.005 MeV is the best value determined from all the coincidence experiments. This value is much less than that (4.4 units) reported for the singles measurements. It has already been pointed out that the decay of this peak in the single-crystal spectra indicated much more of the 169-day species than did most of the other gamma rays. Further, an examination of Column 5 of Table I reveals that the combined q values for all the gamma rays coincident with the 217-keV transition are much too small to account for its single-crystal intensity.

Since a 217-keV ground-state transition in W^{184} seemed quite improbable, it was felt that perhaps this gamma ray may be associated with a metastable state at some higher energy. However, this was shown not to be the case as a delayed coincidence measurement between the 217- and 894-keV gamma rays gave essentially the same delay curve as that obtained for the prompt annihilation radiation of Na^{22}.

Having shown that most of the 217-keV gamma-ray intensity is not associated with W^{184} levels, and as both the single-crystal and the coincidence data indicate that there are two isomeric states of Re^{184}, it therefore appears reasonable to conclude that a 217-keV gamma-ray depopulates the 169-day isomeric state.

The 163-keV transition is also assumed to be associated with Re^{184} levels for the following reasons: (1) The possibility that this 163-keV gamma ray is from Re^{183} is very remote since there was no evidence for any other gamma rays to indicate the presence of Re^{183} (Re^{183} has intense gamma transitions at about 160 keV); (2) the extensive chemical purification employed virtually eliminates the possibility that it arises from other impurities; (3) this gamma ray followed only a 169-day half-life; and (4) within the experimental error it was not found to be in coincidence with any of the gamma rays assigned to W^{184}. If it is assumed that the moment of inertia for the ground-state rotational band of Re^{184} is similar to that of W^{184}, it is not unreasonable from an energy standpoint to conclude that the 163-keV gamma ray is the transition from the first excited level (4−) in Re^{184} (for a discussion of the spin assignments, see Sec. VI). Thus, the evidence seems to lend support for a Re^{184} isomeric level with associated transitions as indicated in Fig. 13. The transition between the 217- and 163-keV levels is expected to be highly converted, explaining its absence in the coincidence data. The change in relative gamma-ray intensities with time for all the spectra indicates that there is a small amount of direct population of W^{184} levels by this 217-keV isomeric state.

It is true that neither Gallagher *et al.*[7] nor Harmatz *et al.*[8] identified such a gamma ray with the decay of Re^{184}, but presumably this is because of the difficulties introduced by the presence of Re^{183} in their sources.

VI. DISCUSSION

At least qualitatively, the odd-proton and odd-neutron states in deformed odd-odd nuclei can now be explained as just the states observed in the adjacent odd-mass nuclei; hence, the states of the odd-odd nucleus are also describable in terms of Nilsson[23,24] wave functions.[25,26]

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[23] S. G. Nillson, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. **29**, No. 16 (1955).

[24] B. R. Mottelson and S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. **1**, No. 8 (1959).

[25] C. J. Gallagher and S. A. Moszkowski, Phys. Rev. **111**, 1282 (1958).

[26] I. Perlman, *Proceedings of the International Conference on Nuclear Structure, Kingston, 1960*, edited by D. A. Bromley and E. Vogt (University of Toronto Press, Toronto, 1960), Chap. 6, p. 547.

Based on the observations in nearby nuclei, the odd proton in Re^{184} is expected to occupy the orbital $5/2+[402]$ and the odd neutron, $1/2-[510]$, where the first term indicates the value of K, the second designates the parity, and the three terms in brackets give the respective asymptotic quantum numbers N, n_z, and Λ. The coupling rules of Gallagher and Moskowski[25] then predict that the ground state of Re^{184} is $3-$. A qualitative check on this assignment is provided by a determination of the reduced transition probabilities for electron capture to the $K=2$, $I=2+$, $3+$, and $4+$ γ-vibrational states in W^{184} (here it is assumed that all direct population of these three states results from the $3-$ state of Re^{184}). The 1.33-MeV W^{184} level is depopulated by a single transition of 0.97-MeV. From the decay rate of this gamma ray it is concluded that the 1.33-MeV level is also fed by electron capture from only the $3-$ state of Re^{184}. The energy of this state is therefore assumed to be the lower limit for the energy separation between the Re^{184}-W^{184} ground states, in close agreement with the energy separation of 1.325 MeV determined by Gallagher *et al.*[7] If this value is used for the approximate ground-state energy separation, the reduced transition probabilities, which are given by the inverse of the ft values, are in the ratio 0.10/0.32/1 for electron capture to the $K=2$, $I=4+$, $3+$, and $2+$ states. This is a quite favorable comparison with the theoretical values 0.05/0.35/1, implying that a spin of $3-$ is probably correct for the Re^{184} ground state.

Although the experimental data tend to support the isomeric levels in Re^{184} as shown in Fig. 13, it is somewhat difficult to understand this isomeric pair on the basis of the expected Nilsson states[23 24] as they appear in neighboring nuclei. In W^{183}, intrinsic states for the 109th neutron have been assigned[24,27] as $1/2-[510]$ for the ground state, $3/2-[512]$ at 209 keV, $9/2+[624]$ at 309 keV, and $7/2-[503]$ at 453 keV. In Re^{183}, the 75th proton ground state is $5/2+[402]$ and the following excited low-lying intrinsic states are observed: $9/2-[514]$ at 496 keV and $7/2+[404]$ at 851 keV.

Of the several possible ways for these available orbitals to form low-energy states in Re^{184}, only two appear promising in terms of explaining a 169-day isomeric level at 217 keV. One is by promoting a neutron from the $1/2-[510]$ state to the $9/2+[624]$ state, giving a $7+$ assignment. In the second, the assignment is $9-$ formed by promoting a proton from the $5/2+[402]$ to the $9/2-[514]$ state and a neutron from the $1/2-[510]$ to the $9/2+[624]$ state. From energy considerations, the $7+$ assignment is preferred, although not indicated on the decay scheme. The level at 163 keV is assumed to be the $4-$, first excited level of the ground-state band.

The total internal conversion coefficient of the 111-keV transition, which has been assigned as pure $E2$,[7,8,11] has been determined in the present work in three different ways. The first of these involves simply an intensity balance of the gamma rays entering and leaving the 111-keV level. The value obtained in this manner is $\alpha(\text{total})=2.74\pm0.04$. The other two ways are obtained from the q values in Table I for the 111-keV gamma ray in coincidence with single-channel window settings of 793 and 902 keV. In the case of the latter energy, it was necessary to correct the observed q value of 0.073 to just the number of 0.894-MeV gamma rays present (see decay scheme). These latter two types of experiments gave respective total internal conversion coefficients of 2.89 ± 0.30 and 2.85 ± 0.30. From these three values, an average $\alpha(\text{total})=2.85\pm0.35$ is determined. The errors here are conservative estimates, and it is felt that the average value of the conversion coefficient is probably more accurate than indicated. In any case the average value is in good agreement with the theoretical value for the total electric quadrupole conversion coefficient, $\alpha_2(\text{total})=2.67$, predicted by Rose[28] and by Sliv and Band.[29]

From the spectra in coincidence with 384, 539, and 641 keV, it is also possible to find the total internal conversion coefficient of the 253-keV transition since each of the three gating gamma rays cascades via the 364-keV level. The values obtained from the three coincidence experiments are in good agreement and yield an average $\alpha(\text{total})=0.36\pm0.06$. Angular correlation corrections have not been applied to the coincidence quotients used in obtaining this value, but these would not be expected to have an appreciable effect on the answer. An intensity balance of the transitions into and leaving the 0.364-MeV level gives a somewhat higher value for $\alpha(\text{total})$, but this is considered less reliable because of the compounding of errors from the several low-intensity gamma rays involved.

Here we see that for the 253-keV transition, there is a large variation between the experimental total $E2$ conversion coefficient and the predicted value $\alpha(\text{total})=0.14$.[28,29] This is not in agreement with the results of Gallagher *et al.*[7] They found that by considering both the 111- and 253-keV transitions as pure $E2$ and by normalizing to the theoretical conversion coefficient for the L_{II} line of the former, all other conversion lines for both transitions agreed with theory.

Although possible, it is difficult to attribute such a large disagreement between the present results and theory solely to experimental error. It is conceivable that there is another ~250-keV gamma ray elsewhere in the scheme, although the internal consistency of the

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[27] C. J. Gallagher, Jr., and H. L. Nielsen, Nucl. Phys. **24**, 422 (1961).

[28] M. E. Rose, *Internal Conversion Coefficients* (North-Holland Publishing Company, Amsterdam, 1958).

[29] L. A. Sliv and I. M. Band, Leningrad Physico-Technical Institute Report, 1956 [translation by P. Axel, Report 57 ICC KL, issued by Physics Department, University of Illinois, Urbana, Illinois (unpublished)].

various coincidence experiments involving the 253-keV transition tend to disfavor such a possibility.

No attempt is made at interpreting the implications of the observed discrepancy, but if it is indeed real, it is a very interesting point. Clearly, there is need for a more detailed study of this feature by such means as gamma-electron coincidence experiments.

In the earlier discussion (Sec. V) on the reduced $E2$ transition probabilities for gamma-ray decay from members of the γ-vibrational band to the ground-state rotational band, it was pointed out that deviations from the theoretical predictions often occur. In a number of cases,[30–35] it has been possible to explain the observed intensity ratios by assuming a mixing of the two bands. The effect of this admixture can be expressed in terms of one parameter z[30] which is

$$z=(Q_{00}/Q_{20})\epsilon(24)^{1/2}. \qquad (2)$$

Q_{00} is proportional to the transition amplitude for transitions within a band (this is the same as the intrinsic static quadrupole moment), Q_{20} is proportional to the transition amplitude for transitions from the $K=2$ band to the $K=0$ band, and ϵ is the reduced amplitude i.e. the amplitude apart from factors depending only on the spin, of the admixture of $K=2$ into the wave function of the 2+ state of the ground-state band. Since Q_{00} represents enhanced $E2$ transitions of the order of 100 single-particle units and Q_{20} is found[16,36,37] from Coulomb excitation experiments to be less than 10 single-particle units, only a small value of ϵ is necessary to alter the expected transition probabilities.

To determine the parameter z, both the numerator and denominator of the right-hand side of Eq. (1) are multiplied by the appropriate correction factors $f(f,I_i,I_f)$[38]; when this is equated to the experimental value, the expression may be solved for z. If the deviations of the uncorrected theoretical branching ratios are actually due to a common admixture in the γ-vibrational band and the ground-state rotational band, then a single value of z should bring all of the theoretical ratios for the transitions between these two bands into agreement with the experimental values. In Table III are shown the results when $z=0.041$ is used. The excellent agreement between the corrected theoretical ratios and the experimental values is gratifying although it must be admitted that the consistency is much better than the accuracy of some of the experimentally determined gamma-ray intensities justify. Nevertheless, the present results when coupled with the numerous other recent similar findings[30–35] tend to support the contention that a common admixture in the rotational bands causes the disparity between theoretical and experimental branching ratios.

TABLE III. Comparison of theoretical branching ratios, of theoretical branching ratios corrected for $z=0.041$, and of experimental values for transitions between the γ-vibrational band and the ground-state rotational band of W^{184}.

	Uncorrected theoretical value	Corrected theoretical value	Experimental value
$B(2\rightarrow 4)/B(2\rightarrow 2)$	0.050	0.080	0.085
$B(2\rightarrow 0)/B(2\rightarrow 2)$	0.70	0.55	0.57
$B(3\rightarrow 2)/B(3\rightarrow 4)$	2.50	1.48	1.43
$B(4\rightarrow 2)/B(4\rightarrow 4)$	0.34	0.18	0.17
$B(4\rightarrow 6)/B(4\rightarrow 4)$	0.09	0.17	0.2

It is interesting to further compare this result for W^{184} with the value $z=0.03$[39] found for W^{182}. These values of the parameter z simply reflect the increased rotation-vibration interaction as we begin to move out of the region of strong deformation. Extrapolating to the case of W^{186}, it may be presumed that an examination of these levels will reveal an even larger value of z.

Energy displacements in the ground-state rotational band are also expected as a result of this mixing between bands. Nielsen[35] has recently calculated the resulting energy displacements for a number of nuclei and compared the results with the corresponding values of B, the parameter associated with the deviations from the $I(I+1)$ energy dependence for the energies in the ground-state rotational band

$$E=\frac{\hbar^2}{2\mathcal{I}}I(I+1)+BI^2(I+1)^2+\cdots. \qquad (3)$$

The mixing of the bands gives rise to energy displacements to the ground-state rotational energies

$$\Delta E=\epsilon^2I^2(I+1)^2(E_{22}-E_{02}), \qquad (4)$$

where $E_{22}-E_{02}$ is the difference in energy between the two 2+ states. ϵ can be found from Eq. (2)

$$\epsilon=z\frac{Q_{20}}{Q_{00}(24)^{1/2}}=z\left(\frac{1}{24}\frac{B(E2,00\rightarrow 22)}{B(E2,00\rightarrow 02)}\right)^{1/2}.$$

For W^{184}, the Coulomb excitation results of McGowan and Stelson[16] were used to get a value $\epsilon=0.00163$. From

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this it is found that

$$\Delta E/I^2(I+1)^2=2.11\text{ eV}.$$

The value of the parameter B is 23.7 eV, as determined from the energies of the 2+ and 4+ levels of the ground-state band in W^{184}. Here the indications are that the W^{184} deviations in the ground state from an $I(I+1)$ energy dependence are in only a small part due to coupling to the γ-vibrational band, a result in complete accord with the systematic analysis of twelve cases by Nielsen.[35]

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Bombardment of C^{12} by Li^6 Ions[*]

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Thin, self-supporting carbon films have been bombarded by Li^6 ions with an incident energy of 3 MeV. Relative angular distributions have been determined for alpha particles leading to the ground state of N^{14}, deuterons to the ground state of O^{16}, and protons to the second, third, and fourth excited states of O^{17}.

In this experiment, C^{12} was bombarded by 3-MeV ions of Li^6 from a Van de Graaff accelerator. The positive-Q reactions resulting from this bombardment are:

$$\begin{aligned}Li^6+C^{12}\rightarrow{}&\alpha+N^{14}+8.79\text{ MeV},\\&p+O^{17}+7.60\text{ MeV},\\&d+O^{16}+5.68\text{ MeV},\\&n+F^{17}+4.05\text{ MeV},\\&n+p+O^{16}+3.45\text{ MeV}.\end{aligned}$$

A rotating solid-state detector was used to detect and identify the charged light particles produced, the energy response of the detector being calibrated with the alpha particles from ThC and ThC′. A 256-channel analyzer sorted the amplified output pulses from the detector. Relative angular distributions were measured for the alpha leading to the ground state of N^{14}, the deuteron to the ground state of O^{16}, and protons to the second, third, and fourth excited states of O^{17}.

Although light particles leading to other excited levels were identified, the angular distributions were not determined because of limitations in the resolution of the detector.

Measurements were made with Dearnaley-type[1] targets of natural carbon. The target spot was approximately 0.040 in.×0.100 in. in size, and was viewed by the detector through an acceptance angle of ±2.5°. Both a monitor detector and a Faraday cup, the latter collecting ions which passed through the target, were used to normalize the angular yield data.

Retractable foils of various thicknesses could be inserted between the detector slit and the detector proper. The charged particles were identified by noting their shift in effective energy as different absorbers of known stopping power were inserted in the beam of reaction products and by their shift in energy with angle of observation. Typical particle spectra for two different absorbers are shown in Fig. 1. Such spectra were obtained for laboratory angles from 30° to 150° in 10° intervals. The resulting angular distributions are illus-

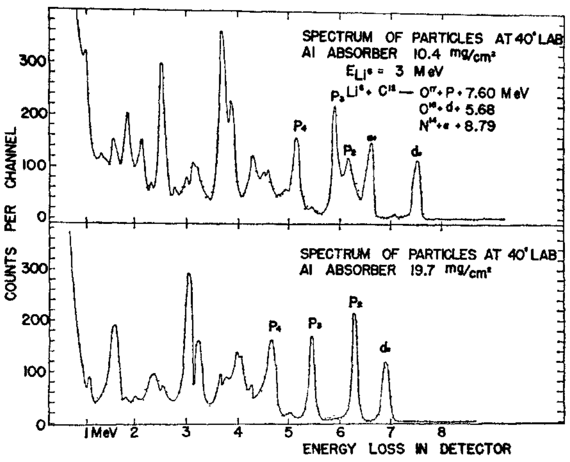

FIG. 1. Typical particle spectra.

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