(A4) to (A3) yields

$$\mathcal{H}=\bar{\psi}(\boldsymbol{\gamma}\cdot\mathbf{p}+\kappa_N)\psi+\kappa_m\bar{\phi}\beta_0^2\phi+\bar{\phi}\boldsymbol{\beta}\cdot\mathbf{p}(1-\beta_0^2)\phi-fj_A\bar{\phi}\beta_0^2\eta_A$$
$$=\mathcal{H}_0^N+\kappa_m\bar{\phi}\beta_0^2-(\mathbf{p}\bar{\phi}\boldsymbol{\beta})(1-\beta_0^2)\phi-fj_A\bar{\phi}\beta_0^2\eta_A, \quad (A5)$$

where, in the second form of (A5), we have integrated by parts, assuming, in fact, that we are computing the total hamiltonian. Another application of (A4) now yields, after some rearrangement and use of the fact that $\beta_0\beta_k\beta_0=0$,

$$\mathcal{H}=\mathcal{H}_0^N+\mathcal{H}_0^m+\mathcal{H}^{Nm}, \quad (A6)$$

where

$$\mathcal{H}_0^m=\kappa_m\bar{\phi}\beta_0^2\phi+\kappa_m^{-1}p_k\bar{\phi}\beta_0^2\beta_k\beta_l\beta_0^2p_l\phi \quad (A7)$$

is the hamiltonian for the free Kemmer field, and

$$\mathcal{H}^{Nm}=-fj_A\bar{\phi}\beta_0^2\eta_A-f\kappa_m^{-1}p_k\bar{\phi}[\beta_k-\beta_k\beta_0^2]\eta_Aj_A \quad (A8)$$

is the interaction hamiltonian.

Equation (A8) may be put into a form more perspicuous for our purposes by noting that the summation over k in the second term may be extended to a summation over the fourth index. We then apply

$$p_\mu\bar{\phi}\beta_\mu=\kappa_m\bar{\phi}-f\bar{\eta}_Aj_A. \quad (A9)$$

The result is

$$\mathcal{H}^{Nm}=-fj_A\bar{\phi}\eta_A+(f^2/\kappa_m)j_B\bar{\eta}_B(1-\beta_0^2)\eta_Aj_A$$
$$=-fj_A\bar{\eta}_A\phi+(f^2/\kappa_m)j_B\bar{\eta}_B(1-\beta_0^2)\eta_Aj_A. \quad (A10)$$

In this form it is seen that the interaction hamiltonian consists of the negative of the coupling term in the lagrangian plus a contact interaction. The latter contributes only when β_0 has the eigenvalue zero. Using the methods of Sec. VI, it may be shown that (A10) leads to an interaction energy which contains no contact interactions. In particular, in the case in which $\gamma_A=I$, the interaction energy vanishes identically.

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Disintegration Scheme of Re^{186}

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The radiations from Re^{186} have been studied by means of beta-ray spectrometers and scintillation counting techniques. It has been found that Re^{186} decays both by beta-emission and by K-capture. Three partial beta-ray spectra of 1.07-, 0.93-, and 0.3-Mev maximum energies have abundances of 76, 19, and 0.4 percent, respectively, and lead to the ground state and 137- and 627-kev excited states of Os^{186}. Two K-capture branches of 3 and 2 percent abundances lead to the ground state and a 123-kev excited state of W^{186}. Transitions between these states give rise to electric quadrupole gamma-rays of 137 and 123 kev and other relatively weak magnetic dipole gamma-rays of 764- and 627-kev energy. A decay scheme in which spins and parities are assigned to all the levels is proposed.

I. INTRODUCTION

THE 90-hour activity of Re^{186} which is strongly induced in rhenium by slow neutron capture is known[1–3] to emit both beta and gamma-rays. It seems well established[4] that the maximum beta-ray energy is 1.07 Mev, but there is some doubt[3] that the spectrum is simple. A number of gamma-rays have been reported and, while the 137-kev line was observed by most workers, the evidence for the existence of other lines was conflicting.

In the work presented in this paper, it will be shown that the disintegration of Re^{186} proceeds by both beta-ray emission and K-capture. Both decays are found to be complex and associated with the emission of gamma-rays and conversion electrons. Although the experiments using different techniques are strongly correlated, they will be described in separate sections; one dealing with spectrometer measurements, the other with coincidence absorption experiments.

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[1] Cork, Shreffler, and Fowler, Phys. Rev. **74**, 1657 (1948).
[2] Beach, Peacock, and Wilkinson, Phys. Rev. **76**, 1585 (1949).
[3] P. J. Grant and R. Richmond, Proc. Phys. Soc. (London) **A62**, 573 (1949).
[4] L. M. Langer and H. C. Price, Phys. Rev. **76**, 641 (1949).

II. SPECTROSCOPIC MEASUREMENTS

The sources used were pile-irradiated Re metal powder obtained from Oak Ridge. Experiments on these sources were performed about a week after irradiation, thus allowing the 19-hour Re^{188} activity to decay to less than one percent of the total activity.

The pulse-height distribution from a scintillation counter irradiated with the Re gamma-rays was followed for a period of three months. After Re^{186} had decayed to less than one-thousandth of its initial activity, a 1-Mev gamma-ray was found to be present in the remaining source. Both the energy and decay of this gamma-ray are consistent with the assumption that the 50d-Re^{184} had been produced in the irradiation but was, at the time of our experiments, contributing less than 0.01 percent of the total activity.

A. Conversion Electron Spectrum

The spectrum observed with a photographic 180° spectrograph showed the existence of conversion lines from a 137-kev gamma-ray converted in osmium, and also of lines from a 123-kev gamma-ray converted in wolfram. Three gamma-rays have been observed by Cork, Shreffler, and Fowler[1] in this energy region, but

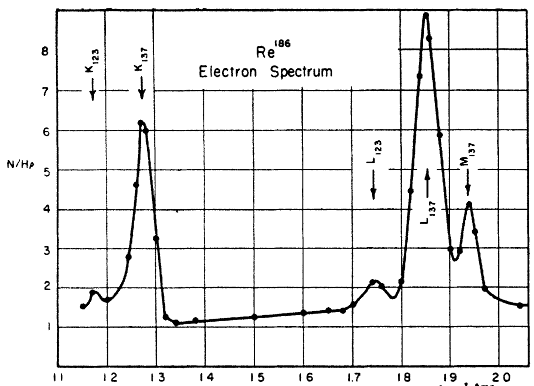

FIG. 1. Electron spectrum of Re[186] in the energy region between 50 and 150 kev.

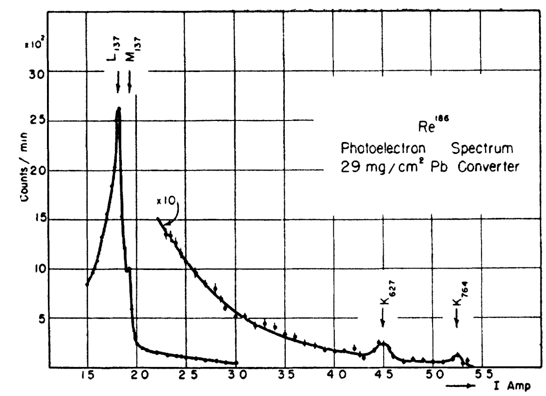

FIG. 3. Photoelectron spectrum of Re[186] using a lead converter.

there is no indication in our spectrum of a third gamma-ray as suggested by these workers.

The relative intensities of the conversion lines were derived from the spectrum shown in Fig. 1, which was obtained using a lens spectrometer in conjunction with a thin source ($\sim$0.1 mg/cm^2). We estimate that the conversion lines of the 137-kev transition are approximately ten times more intense than the corresponding lines of the 123-kev gamma-ray. The K/L ratio of the 137-kev transition is 0.6 ± 0.1 and the L/M ratio is 4.4.

Combining the values obtained by different observers, we consider 0.057 as the best value for the ratio of the number of 137-L electrons to the total number of beta-rays. (This value is corrected for the contribution of 123-L electrons which were not resolved by other workers from the 137-L conversion line.)

From the higher resolution spectrum of the 180° instrument it is observed that the 137-L_{I} line is approximately as intense as the 137-L_{III} conversion line.

B. Beta-Ray Spectrum

The beta-ray spectrum of Re[186] was measured using a lens spectrometer, and considerable care was taken to obtain accurate determinations of the points at the upper end of the spectrum. The Fermi plot of this spectrum, which is given in Fig. 2, exhibits a small change of slope in the region of 900 kev. Analysis of the plot, assuming allowed shape spectra, indicates an 83 percent component of upper end point 1.07 Mev and a remaining 17 percent component of upper end point 0.93 ± 0.05 Mev. The presence of a partial spectrum of this lower energy agrees qualitatively with the results of Grant and Richmond.[3]

C. Photoelectron Spectrum

A number of photoelectron spectra were taken in the lens spectrometer using different atomic number converters. Curves for lead and tin are given in Figs. 3 and 4. They confirm the existence of gamma-rays of 137 and 123 kev and, in the case of lead, point to the presence of two equally intense gamma-rays of 627 and 764 kev. These gamma-rays can be identified with the hard component reported on the basis of absorption experiments by Cork, Shreffler, and Fowler,[1] and also by Grant and Richmond.[3] No indication of either a 212-[2] or a 275-kev[3] gamma-ray was obtained. The number of quanta of these energies is certainly less than one percent of the number of 137-kev quanta. The K-photoelectron line of a 275-kev gamma-ray, and the L-lines of 275- and 212-kev gamma-rays, would appear in the spectrum of Fig. 3 between 2.2 and 2.8 amp. The

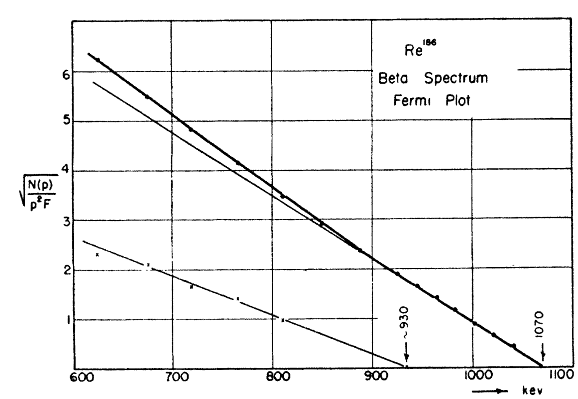

FIG. 2. Fermi plot of the beta-ray spectrum of Re[186].

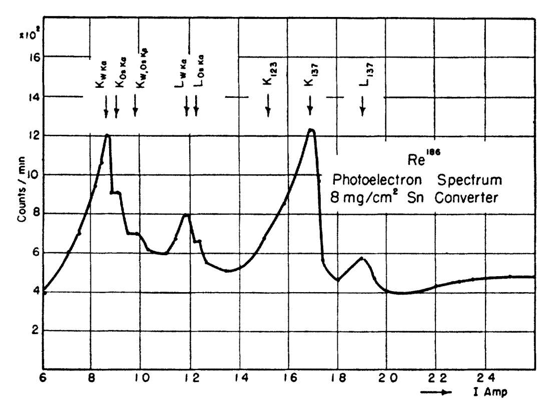

FIG. 4. Photoelectron spectrum of Re[186] using a tin converter.

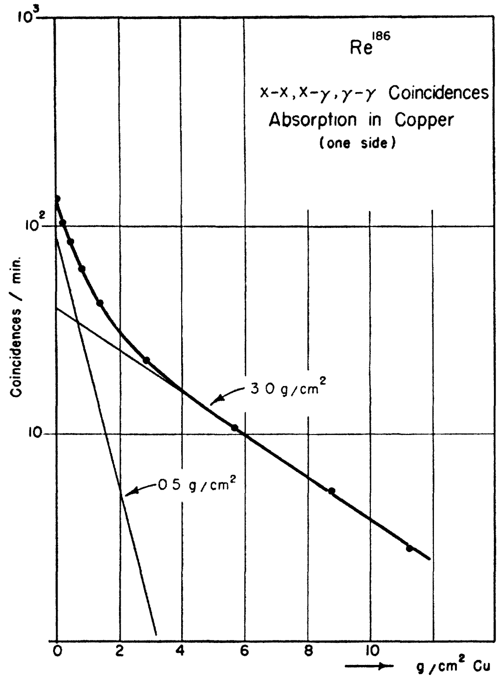

FIG. 5. Absorption of x–x, x–γ, and γ–γ coincidences by copper absorbers in front of one counter.

K-line of a 212-kev gamma-ray would also appear in the spectrum of Fig. 4 at a current of 2.31 amp. The strong line in the Pb photoelectron spectrum interpreted by Beach, Peacock, and Wilkinson[2] as the *K*-line

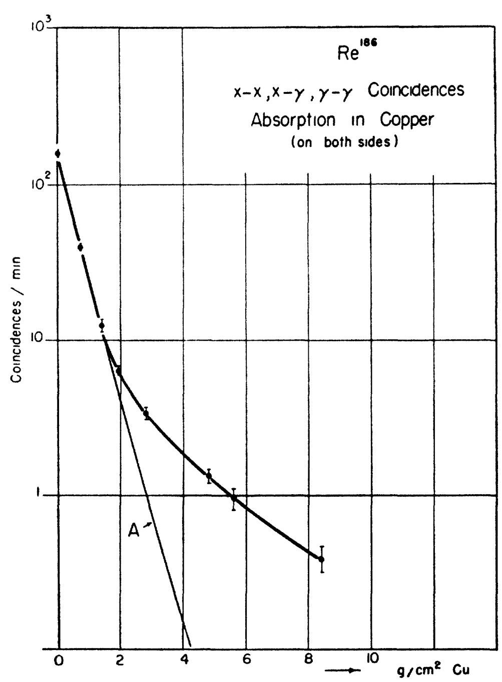

FIG. 6. Absorption of x–x, x–γ, and γ–γ coincidences by copper absorbers in front of both counters. Curve A was calculated assuming the absence of γ–γ coincidences.

of a 212-kev gamma-ray is really the *L*-line of the 137-kev gamma-ray. The high intensity of the *L*-line relative to the *K*-line in their Pb photoelectron spectrum is attributable to the difference in degradation of the two photoelectron groups in the thick converter.

From the photoelectron spectrum obtained with a thin (5 mg/cm^2) gold converter, the ratio of the intensities of the 137- and 123-kev gamma-rays is estimated to be 9 ± 2.

An important feature of the tin photoelectron spectrum is the appearance of partly resolved lines due to wolfram and osmium *K* x-rays. The existence of wolfram *K* x-rays proves that Re^{186} decays by *K*-capture, a process already suggested by the conversion of the 123-kev gamma-ray in wolfram. From the photoelectron spectrum we estimate the wolfram *K* x-rays to be approximately 1.5 times more intense than the osmium *K* x-rays.

III. COINCIDENCE ABSORPTION EXPERIMENTS

Sodium iodide scintillation counters were used in these experiments. Crystal thicknesses varied from 0.5 to 30 mm, depending on the radiation being investigated. Counting efficiencies for different energy radiations were estimated from total gamma-ray absorption cross sections, assuming complete detection of secondary electrons. The resolving time of the coincidence circuit was 1.2×10^{-7} second.

A. Gamma-Gamma-Coincidences

After absorbing all electrons from the source in beryllium, the coincidence rate between electromagnetic radiations was measured as a function of the thickness of copper absorber. The curves of Figs. 5 and 6 were obtained with absorbers in front of one counter and in front of both counters, respectively. The curve of Fig. 5 can be decomposed into two parts with half-value thicknesses of 0.5 and 3.0 g/cm^2 copper, values which are consistent with the absorption of x-rays (~60 kev) and gamma-rays (130 ± 20 kev). In the experiment using absorbers on one side, the large intensity of the x-ray component at zero absorber thickness indicates a large contribution of x–x coincidences.

From the strong absorption exhibited in the experiment where absorbers were placed in front of both counters (Fig. 6), we conclude that x-rays are involved in practically all of the observed coincidences. Curve A is drawn on the assumption that all coincidences are of the x–x and x-gamma types. The departure of the measured points from this curve at large absorber thicknesses indicates, however, that there remains a small percentage of true gamma-gamma-coincidences, which we ascribe to the 137- and 627-kev groups.

Having established the existence of *K*-capture in the Re^{186} decay we looked for the presence of annihilation radiation which would indicate positrons. The counters were biased to detect only gamma-rays above approximately 200 kev, and the gamma-gamma-coincidence rates were determined with the counters at 180° and 90° to each other. With approximately one millicurie of Re^{186}, the 180° and 90° coincidence rates did not differ by more than 0.5 coincidences per minute. From the strength of the source and the over-all detection efficiency it is estimated that there is less than one positron, if any, in 10^7 disintegrations.

B. Beta-Gamma-Coincidences

With all absorbers removed from one counter, the coincidence rate as a function of the thickness of copper absorber in front of the other counter was determined. After the subtraction of x–x and x–gamma coincidence rates, the curve shown in Fig. 7 was obtained. This curve indicates that some of the beta-rays are coincident with a gamma-ray of 130±20 kev (3.4 g/cm²) and an x-ray of ~60 kev (0.5 g/cm²). The number of beta-gamma-coincidences per beta-ray is approximately four times less than the rate to be expected if all beta-rays are followed by a gamma-ray of 137 kev. Since McGowan[5] has shown that the 137-kev excited state has a life-time of less than 2×10^{-9} second, the low beta-gamma-coincidence rate cannot be ascribed to a lifetime which is longer than the coincidence resolving time (1.2×10^{-7} second), and must be attributed to a branching of the beta-decay.

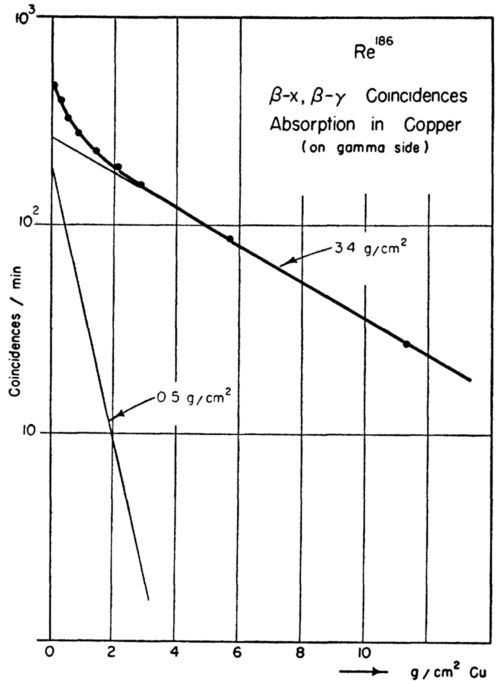

FIG. 7. Absorption of β–x and β–γ coincidences by copper absorbers in front of the γ-ray counter.

IV. DISCUSSION

The foregoing experiments lead immediately to the main features of the decay scheme shown in Fig. 8. Further details of this scheme will now be discussed.

A. Multipolarity of Gamma-Rays

The value of 0.03 for the K-conversion coefficient of the 137-kev gamma-ray, which was reported by Beach, Peacock, and Wilkinson,[2] is approximately five times less than the minimum theoretical value for the conversion of a gamma-ray of this energy.[6] According to the present suggested decay scheme, the number of K-conversion electrons has to be compared, not with the total beta-ray spectrum, but with the 17 percent branch, and this leads to a value of the order 0.5 for the K-conversion coefficient of the 137-kev gamma-ray.

Owing to the uncertainties with which the abundance of the partial beta-ray spectrum and the K/L ratio of the 137-kev gamma-ray are known, the K-conversion coefficient obtained from spectroscopic data is rather inaccurate. A more precise value can be obtained from the beta-gamma-coincidence absorption data of Fig. 7. The magnitudes of the 137-kev and the osmium K x-ray components at zero absorber thickness, corrected for fluorescent yield and counter efficiencies, give directly a value of 0.35±0.1 for the K conversion coefficient of the 137-kev gamma-ray. Comparing this value with the extrapolated theoretical conversion coefficients of Rose,[6] agreement is only possible for electric quadrupole for which the theoretical value is 0.43.

Since the ratios of the numbers of conversion electrons as well as the numbers of gamma-rays of the 137- and 123-kev transitions are identical to within the experimental error, it is inferred that the two gamma-rays, which are of much the same energy, are of the same multipole order.

As mentioned above, the 137- and 123-kev transitions are electric quadrupoles; and, therefore, if it is assumed, that the ground states of the even–even nuclei, Os^{186} and W^{186}, have spin 0, the 137- and 123-kev levels must have spin 2 and the same parity as the ground states.

From a single absorption experiment the hard

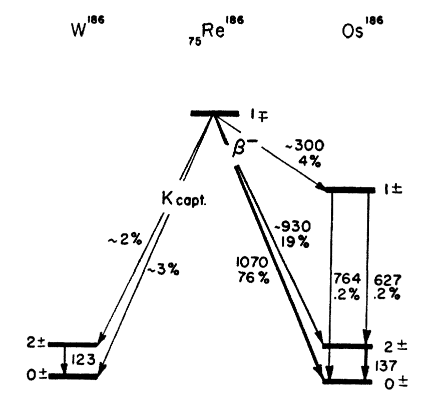

FIG. 8. Proposed disintegration scheme of Re^{186}. Transition energies are given in kev.

[5] F. K. McGowan, Phys. Rev. **79**, 404 (1950).
[6] M. E. Rose and others, "Tables of K-conversion coefficients" (unpublished).

gamma-ray component was estimated to be 25 times weaker than the 137-kev gamma-ray. Since the total conversion coefficient of the 137-kev transition is 1.06, the 137-kev gamma-rays are emitted in 9 percent of the Re^{186} disintegrations, and consequently the hard gamma-rays are emitted in approximately 0.4 percent of the disintegrations.

The difference of 137 kev between the energies of the two hard gamma-rays suggests that they occur on the beta-ray side of the Re^{186} decay. Furthermore, since the two gamma-rays are of comparable intensities and differ only slightly in energies, both transitions must be of the same multipole order. The 764-kev excited state must therefore have either spin 1 or 2. In the next section it will be shown that this level has the same parity as the ground state, and thus there remain only two possible assignments for the 764-kev level, one of which can be ruled out using the following argument. An assignment of spin 2 would make the 627-kev transition a magnetic dipole and the 764-kev transition an electric quadrupole. According to a recent analysis of multipole radiation by Weisskopf[7] the magnetic dipole transition would be favored in comparison with the electric quadrupole transition and this is in contradiction with experiment. The most probable spin value of the 764-kev state is therefore 1, thus characterizing the two hard gamma-rays as magnetic dipole radiations.

B. Beta-Ray Transitions

On the basis of spectroscopic measurement it was shown that there is a 17 percent lower energy branch of the beta-ray spectrum. As this analysis assumed allowed shapes of the beta-spectra, it was important to substantiate the branching ratio by an independent measurement. A value of the branching ratio can be obtained from a combination of the following data:

(1) The ratio of the number of K-conversion electrons of the 137-kev gamma-ray to the total number of beta-rays:

$$N_K/(N_{\beta 1}+N_{\beta 2})=0.034.$$

(2) The K-conversion coefficient determined from the beta-gamma-coincidence data: $N_K/N_\gamma=0.35$.

(3) The total conversion coefficient: $N_K+N_L+N_M/N_\gamma=1.06$.

From these values the ratio of the low energy beta-group to the total number of beta-rays, $N_{\beta 1}/(N_{\beta 1}+N_{\beta 2})$, is found to be 0.20. The good agreement of this value with that derived from the Fermi plot probably indicates that both partial spectra have allowed shapes.

Using the observed intensities of the partial beta-ray spectra, the following ft-values[8] have been obtained: $(ft)_{0.3\text{ Mev}}=1.6\times 10^8$; $(ft)_{0.93\text{ Mev}}=1.3\times 10^8$; $(ft)_{1.07\text{ Mev}}=0.5\times 10^8$. All three beta-disintegrations are therefore of the same degree of forbiddenness and might be classified as first forbidden. In these circumstances the Re^{186} ground state possesses a parity opposite to that of the three osmium levels reached by beta-disintegrations.

If it is assumed that both partial spectra have allowed shapes, one can tentatively assign spin 1 to the ground state of Re^{186}, since both spin 0 and 2 would lead to either one of the spectra having an α-type shape.[9]

C. K-Capture

Re^{186} decays to some extent by K-capture. The branch leading to the 123-kev level of wolfram comprises approximately two percent of all disintegrations, and there is also a K-capture branch leading to the ground state of W^{186}.

It has been found from the photoelectron experiments that wolfram K x-rays are 1.5 times more abundant than osmium K x-rays. From the intensity of the 137-kev gamma-ray and its K-conversion coefficient it is calculated from osmium K x-rays occur in approximately 3.5 percent of the Re^{186} disintegrations, and wolfram K x-rays in 5 percent of the disintegrations. Thus, K-capture transitions to the ground state of W^{186} occur in 3 percent of the Re^{186} disintegrations.

The observation of an appreciable amount of K-capture leading to the 123-kev level may be taken as indicating that the $Re^{186}-W^{186}$ mass difference must be larger than 200 kev. On the other hand, an upper limit of 1.2 Mev for this mass difference can be deduced from the fact that there is less than one positron in 10^7 Re^{186} disintegrations. For a 2 percent K-capture branch from Re^{186}, the ft-values corresponding to the above energy limits are 7×10^6 and 2.5×10^8, respectively. This implies that the transitions on the K-capture side of Re^{186} are of the same degree of forbiddenness as the beta-ray transitions. Acceptance of this conclusion leads to the assignment of parities for the W^{186} levels as shown in Fig. 8.

[7] Privately circulated notes, to appear as a book on nuclear physics.

[8] E. J. Konopinski, Revs. Modern Phys. **15**, 209 (1943).

[9] C. S. Wu, Revs. Modern Phys. **22**, 386 (1950).