COULOMB EXCITATION OF HIGH-ENERGY NUCLEAR LEVELS IN EVEN ISOTOPES OF TUNGSTEN

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Natural tungsten and samples enriched in W^{182}, W^{184}, and W^{186} were irradiated with α particles having energies from 8.3 to 14.5 Mev. The existence of the following excited states was established: 1.22 Mev in W^{182}, 0.90 Mev in W^{184}, and 0.73 Mev in W^{186}. The reduced probabilities B(E2) of transition to the ground state computed for these levels are 0.051, 0.038, and 0.040, respectively (in units of $e^2 \times 10^{-48}$ cm^4). The assumption that these levels are vibrational levels is discussed.

1. INTRODUCTION

COULOMB excitation of nuclear levels of even isotopes of tungsten has been studied in several papers.[1-3] These authors observed the excitation of the first rotational levels (with quantum numbers 2^+), determined the energies of these levels and the reduced probability for electric quadrupole transition from the ground state to the first rotational state.

Coulomb excitation of the second rotational levels (with quantum numbers 4^+) in even-even nuclei is much more difficult since this process requires the occurrence of an E4 transition. For this reason Coulomb excitation of the second rotational level has as yet not been observed in any even-even nuclei.

But on the basis of the uniform model of the nucleus one should expect that among the excited states of deformed nuclei there should be 2^+ levels located above the first few lowest levels of the first rotational band which is associated with the ground state of the nucleus. The new levels to which we refer are vibrational levels. In addition the quantum numbers 2^+ can occur for some levels of the rotational bands associated with single particle or "pair" excitation (where the latter refers to the simultaneous transition of two nucleons to excited states). Because of the collective character of the vibrational level, the magnitude of the reduced transition probability B(E2) to such a level is larger than the value of B(E2) for a single particle transition, so that the cross section for Coulomb excitation to a vibrational level should be greater than that for excitation of a single particle level.

We have shown in previous papers[4,5] that by using α particles with energy ~ 15 Mev for Coulomb excitation, one can excite levels in various even-even nuclei up to 1.5 Mev excitation. One may expect to excite such levels in the tungsten isotopes if the level energies do not exceed 1.5 Mev. Their excitation is much more probable than excitation of the second level of the lowest rotational band.

Highly excited levels of the tungsten isotopes were not observed in references 1 to 3 because the bombarding particles used in these experiments had low energies, while the cross section for Coulomb excitation of high energy levels depends strongly on the energy of the bombarding particles. Recently,[6] using 5-Mev protons, a level with ΔE = 730 kev in W^{186} was excited.

Experiments in which the level scheme is studied by investigating artificial radioactivity of the corresponding nuclei are of interest in settling the question of the existence of excited levels up to 1.5 Mev in the even tungsten isotopes. Among such experiments we should especially mention reference 7 in which the decay of Ta^{182} was studied. As a result of parallel study of the β and conversion electron spectrum using a β spectrometer, and of the γ spectrum using a bent-crystal spectrometer, these authors succeeded in setting up a complex scheme of levels and transitions in W^{182} and assigning quantum numbers to the levels. The superior resolution of the γ-spectrometer (0.1% for low energy γ rays and approximately 1.5% in the high energy region) enabled them to determine very accurately the relative intensities of individual γ lines, despite the fact that there were a large number of lines

(~30). According to the level scheme of W^{182} proposed in reference 7, this isotope has an excited 2^+ level at $\Delta E = 1222$ kev. The authors note that though the 2^+ assignment seems most likely from the analysis of various facts, it cannot be regarded as confirmed by a direct experiment since the conversion coefficients for transition from this level have not been measured accurately enough. It has been shown[8] using the ratio of the γ intensities emitted in transitions to the ground level and the first and second excited rotational levels, that the 1222-kev level in W^{182} is a γ-vibrational level. The authors of references 9 and 10 used a scintillation spectrometer to determine the energies and relative intensities of the γ rays emitted in the β decay of Ta^{184} and Ta^{186} to W^{184} and W^{186}, respectively. They did not propose level schemes for these nuclei and did not consider the possible quantum assignments of the levels.

On the basis of the uniform model and data on nuclear level systematics, Peker[11] used the information about energies and relative intensities of γ-rays given in references 9 and 10 to construct level schemes for W^{184} and W^{186}. In these level schemes the level at $\Delta E = 900$ kev in W^{184} and the level at $\Delta E = 730$ kev in W^{186} are assigned as γ vibrational levels, i.e., as levels with quantum numbers 2^+.

Our experiments on Coulomb excitation of high energy levels in the even isotopes of tungsten had the following purposes:

(1) To check whether the energy levels mentioned above are excited, and thus to show the existence of these levels directly. The presence of the corresponding γ rays in Coulomb excitation would serve both as a proof that the previously observed γ lines correspond to transtions from these levels to the ground level and not to transitions between higher levels, and as an independent confirmation of the 2^+ assignment for these levels.

(2) To measure the relative intensities of γ rays emitted in transitions from highly excited states to the levels of the lowest rotational band.

(3) To determine the reduced probability for excitation of these levels from the ground state.

2. EXPERIMENTAL METHOD AND TREATMENT OF RESULTS

We used α particles accelerated in a cyclotron for Coulomb excitation of levels of the even isotopes of tungsten. Altogether we used four fixed energies for the α particles: 8.3, 10.2, 13.1, and 14.5 Mev. The targets were 0.25 mm thick foils of natural tungsten and samples enriched in various tungsten isotopes, in metallic powder form, a layer of which was pressed onto a lead backing 50 μ thick. In all cases the target thickness was enough to slow the α particles down to an energy at which the Coulomb excitation cross section was very small.

The beam of α particles extracted from the cyclotron was focused on the target by a system of two magnetic quadrupole lenses. The target was located on the bottom of an insulated metallic container which served as a Faraday cup. An electronic current integrator was connected to the cup. The γ radiation emitted in the de-excitation of the excited nuclear states was studied by means of a scintillation spectrometer. The detecting system consisted of a NaI (Tl) crystal 40 mm in diameter and 40 mm high and a FEU-S photomultiplier; the recording system was a 50-channel pulse-height analyzer.

To prevent loading of the amplifier by the large number of pulses resulting from Coulomb excitation of the first rotational level of the tungsten nuclei and from the characteristic tungsten radiation emitted under the action of the α particles, a 1.8 mm lead absorber was placed between the scintillator and the target.

More detailed information concerning the experimental arrangement is given in reference 4. It also describes the procedure for processing the experimental results. The computations are complicated somewhat by the following fact. As the data to be presented in Sec. 3 show, the de-excitation of highly excited levels in tungsten occurs via two parallel transitions (a $2' \to 0$ transition to the ground state and a $2' \to 2$ transition to the first rotational level). Thus the value of the reduced probability $B(E2)_{0\to 2'}$ for transition from the ground state to the excited state must be computed from the sum of the yields of the γ rays in the $2' \to 0$ and $2' \to 2$ transitions. According to the principle of detailed balancing, the quantities $B(E2)_{2'\to 0}$ and $B(E2)_{0\to 2'}$ are related by the formula

$$(2I_f + 1)\, B(E2)_{2'\to 0} = (2I_0 + 1)\, B(E2)_{0\to 2'}\,.$$

In our case, $I_0 = 0$ and $I_f = 2$, so that

$$B(E2)_{2'\to 0} = {}^1/_5\, B(E2)_{0\to 2'}\,.$$

In Sec. 4 we shall give arguments in favor of the assumption that the $2' \to 2$ transition is mainly electric quadrupole. Making this assumption, we can calculate the value of $B(E2)_{2'\to 2}$ using the formula

$$N_{2'\to 2} / N_{2'\to 0} = (B(E2)_{2'\to 2} / B(E2)_{2'\to 0})\,(\Delta E_{2'\to 2} / \Delta E_{2'\to 0})^5,$$

where N is the intensity of the γ radiation emitted in the corresponding transition and ΔE is the energy of the γ quanta.

The mean life τ of the $2'$ state was computed from the formula

$$1/\tau = 1/\tau_{2'\to 0} + 1/\tau_{2'\to 2}.$$

The values of the partial lifetimes ($\tau_{2'\to 0}$ and $\tau_{2'\to 2}$) were calculated from the values of $B(E2)_{2'\to 0}$ and $B(E2)_{2'\to 2}$ found earlier.

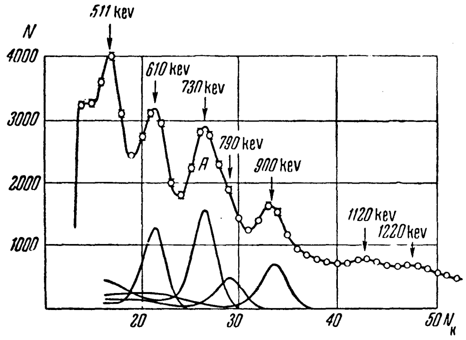

FIG. 1. Instrumental spectrum of γ rays emitted in Coulomb excitation of natural tungsten; $E_\alpha = 14.5$ Mev.

3. RESULTS OF THE MEASUREMENTS

Figure 1 shows the instrumental spectrum of γ lines emitted after Coulomb excitation of natural tungsten.* The lines at 1120 and 1220 kev must be assigned as radiation in W^{182}, emitted in the $2'\to 2$ and $2'\to 0$ transitions. The maxima in the spectrum are shown more clearly in Fig. 2, which gives the instrumental spectrum taken when the lower limit of the circuit transmitting the pulses to the input of the 50-channel analyzer was set so that pulses of relatively low amplitude did not reach the analyzer. The difference in energy of the two γ lines corresponds to the energy of the first rotational level of W^{182}, which is 100.1 kev, according to the data of reference 3.

The line at 900 kev should be assigned to the $2'\to 0$ transition in W^{184}. Since the energy of the first rotational level[3] of W^{184} is 111 kev, the energy of the $2'\to 2$ transition to the first rotational level of W^{184} should be 900 − 111 = 789 kev. Actually we see from Fig. 1 that peak A is composite — on its right edge there is an indication of a peak with ΔE = 790 kev.

The lines at 730 and 610 kev should be assigned to the radiation emitted in the $2'\to 0$ and $2'\to 2$ transitions in W^{186}. The difference in energy of these lines corresponds to the energy of the first rotational level of W^{186}, which is 122.5 kev according to the data of reference 3.

The 511 kev line is apparently annihilation radiation. Positron emitters can be formed in (α, n) reactions on light element impurities in the tungsten.

The theoretical line shapes are shown for the 900, 790, 730, and 610 kev lines in the lower part of Fig. 1; these curves were drawn on the basis of data given in reference 12. The fact that peak A is composite and consists of two peaks with the energies given above is confirmed as usual: when we add the individual peaks with ΔE = 730 and 790 kev shown at the bottom of Fig. 1, we get a composite peak of the same shape as that found in the experiment.

Figures 3 and 4 show the instrumental γ spectra found after Coulomb excitation of targets enriched in W^{184} and W^{186} respectively. The results obtained with these targets give additional proof of the correctness of the identification of the γ lines found in the spectrum of natural tungsten. In fact, when we irradiate a target enriched in W^{184}, only the 790 and 900 kev lines appear, and we see only the 610 and 730 kev lines from a target enriched in W^{186}. Unfortunately the amount of impurities in the enriched samples proved to be considerably greater than in natural tungsten. One can judge the relative amounts of impurities in various targets from the relative intensity of the 511-kev line in Figs. 1 and 4. The increased content of impuri-

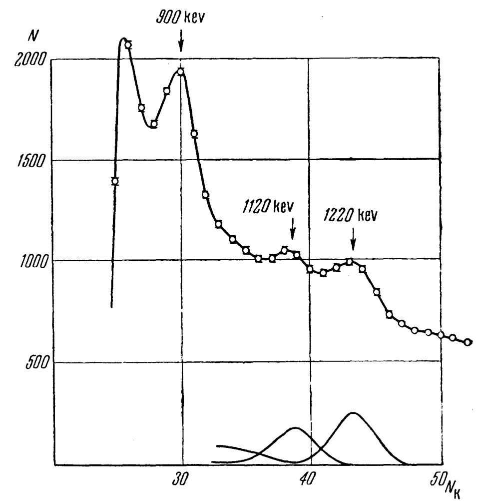

FIG. 2. Expanded spectrum of γ rays emitted in Coulomb excitation of natural tungsten; E_α = 14.5 Mev.

ties caused the peak-to-background ratio for the enriched samples to be almost a tenth of that for natural tungsten. The values of $B(E2)$ found from the experiments with W^{184} and W^{186} differ little from the results obtained with natural tungsten. In view of our previous remarks concerning

*We shall use N_k for the channel number and N for the total number of counts in a channel per microcoulomb in the bombarding beam.

the ratio of effect to background, we used only the data obtained from measurements on natural tungsten targets in calculating the averaged values of $B(E2)_{2'\to 0}$ given in Table I.

The yield of γ quanta from Coulomb excitation of a level drops markedly with increasing excitation energy of the level. Thus in using a sample enriched in W^{182} but containing all sorts of impurities the intensity of the peaks corresponding to deexcitation of the excited level at $\Delta E = 1222$ kev in W^{182} was so small compared to background that the energy of the corresponding γ rays could not be measured reliably.

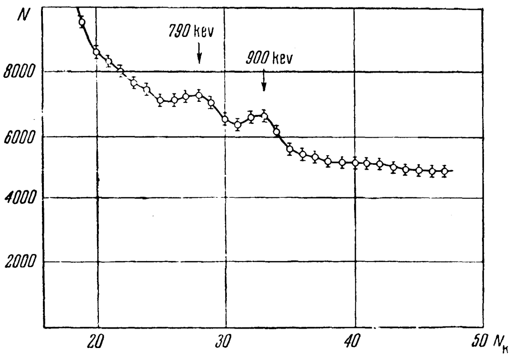

FIG. 3. Instrumental spectrum of γ rays emitted in Coulomb excitation of W^{184}; $E_\alpha = 13.1$ Mev.

The data obtained from Coulomb excitation of natural tungsten are presented in Table I. The values of $B(E2)_{2'\to 0}$ and $B(E2)_{2'\to 2}$ are the averages of data of ten experiments at four different values of E_α in the case of W^{184} and W^{186}, and of the data of four experiments at $E_\alpha = 14.5$ Mev in the case of W^{182}.

The table also gives the ratios $\eta = B(E2)_{2'\to 0}/B(E2)_{2'\to 2}$, the lifetimes of the excited states and, finally, the values of F which is the ratio of the experimental value of $B(E2)_{2'\to 0}$ to the value computed from the formula for single particle transitions on the assumption that the nuclear radius is $R_0 = 1.2\,A^{1/3} \times 10^{-13}$ cm. The standard deviation of the values of $B(E2)_{2'\to 0}$ and $B(E2)_{2'\to 2}$ was less than 10%. The overall error in these quantities due to the arbitrariness in drawing the background curve and to statistical errors amounts to 25% according to our estimates. The error in the ratio η is 15% for W^{186}, 20% for W^{184},

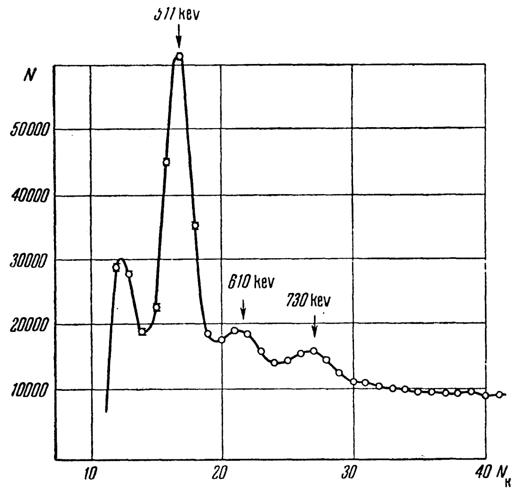

FIG. 4. Instrumental spectrum of γ rays emitted in Coulomb excitation of W^{186}; $E_\alpha = 14.5$ Mev.

and 30% for W^{182}. The error in the value of η for W^{184} and W^{186} is smaller than the error in the individual values of $B(E2)_{2'\to 2}$ and $B(E2)_{2'\to 0}$ because η is affected less by the inaccuracy in drawing the background curve. On the other hand, the overall error in the values of $B(E2)_{2'\to 2}$ and $B(E2)_{2'\to 0}$ for W^{182} is determined to a large extent by statistical errors, so in this case the error in the ratio η will be greater than the errors in the individual values of $B(E2)$.

4. DISCUSSION OF RESULTS

As already mentioned, in the spectrum of γ rays emitted in Coulomb excitation of tungsten nuclei we observed γ rays corresponding to excitation of a level in W^{182} at 1220 kev, a level at 900 kev in W^{184}, and a level at 730 kev in W^{186}. These results show that the 1220, 900, and 730-kev γ lines correspond to transitions to the ground states (and are not emitted in transitions between higher levels), and that these levels can be assigned as 2^+ states. We have thus obtained experimental confirmation of the assumptions made in reference 11 regarding the levels of W^{184} and W^{186} and have found independent additional evidence for the 2^+ assignment of the level with $\Delta E = 1220$ kev in W^{182}.

In Coulomb excitation of nuclei, one can excite single particle and "pair" levels in addition to rotational and vibrational levels. We next discuss

TABLE I

Isotope	$\Delta E_{0\to 2'}$, Mev	$\frac{B(E2)_{2'\to 0}}{e^2}$, 10^{-48} cm^4	$\delta\left(\frac{B(E2)_{2'\to 0}}{e^2}\right)$, %	$\frac{B(E2)_{2'\to 2}}{e^2}$, 10^{-48} cm^4	$\frac{B(E2)_{2'\to 0}}{B(E2)_{2'\to 2}}$	$\delta\left(\frac{B(E2)_{2'\to 0}}{B(E2)_{2'\to 2}}\right)$, %	τ, 10^{-13} sec	F
W^{182}	0.22	0.051	25	0.043	1.2	30	0.38	8
W^{184}	3.90	0.038	25	0.055	0.69	20	2.2	6
W^{186}		0.040	25	0.076	0.53	15	5.6	6

various considerations which must be taken into account in solving the question of the nature of the levels observed in the present work.

It is known that the vibrations excited in axially symmetric nuclei have certain special features.[13] In addition to the quantum number λ, the vibrations are characterized by the quantum number ν which is the projection of the angular momentum of the oscillation along the symmetry axis of the nucleus. For a fixed value of λ, $\nu = 0, \pm 1, \pm 2, \ldots \pm\lambda$.

Unlike the vibrations of a spherical nucleus, for spheroidal nuclei the vibration parameters B_2 and C_2 and consequently the energy of the vibrational state depend not only on λ but also on ν. For $\lambda = 2$ (quadrupole oscillations) the possible types of oscillation of a spheroidal nucleus correspond only to the values $\nu = 0$ and $\nu = \pm 2$, since vibrations with $\nu = \pm 1$ are equivalent to a rotation of the nucleus. Vibrational levels corresponding to $\nu = 0$ are called β vibrations and those with $\nu = \pm 2$ are called γ vibrations.

For rotational bands associated with single phonon excitation, the projection K of the total angular momentum on the nuclear symmetry axis is equal to $|K_0 \pm \nu|$, where K_0 is the value of K in the ground state of the nucleus. For even-even nuclei $K_0 = 0$, so that $K = 2$ for γ-vibrational levels and $K = 0$ for β-vibrational levels. Figure 5 shows the spins and parities of the levels of the rotational bands.

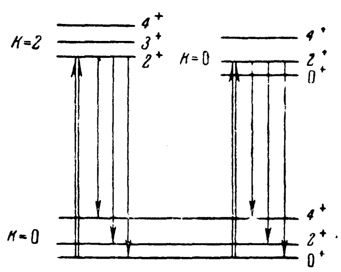

FIG. 5. Level sequence in rotational bands. The lowest band is associated with the nuclear ground state. On the left are excited γ-vibrational states, on the right excited β-vibrational states.

Since the most probable transitions resulting from Coulomb excitation are E_2 transitions, it follows from Fig. 5 that in Coulomb excitation of vibrational levels in even-even nuclei either the second level of the rotational band associated with β vibration or the first level of the band associated with excitation of γ vibration will be excited. Both levels have the same spin value ($I = 2$) and they have the same parity as the ground state, but their K values are different.

It was shown in reference 8 that the ratios of the reduced probabilities for transitions of a given multipolarity from any level to the levels of a rotational band can be expressed in terms of Clebsch-Gordan coefficients for whose calculation we need to know only the values of I and K and the multipolarities of the transitions between the various states. For the case of electric quadrupole transition from a level with $I = 2'$, $K = 2$ to levels with $I = 0$, 2, and 4, and $K = 0$ (which form the rotational band associated with the ground state), these ratios are $0.7:1:0.05$ respectively. If the same levels are reached by transitions from a level with $I = 2'$, $K = 1$ or $I = 2'$, $K = 0$, the ratios are $2.8:1:2.3$ and $0.7:1:1.8$, respectively.

From Table I we see that the ratios of the reduced probabilities determined in the present experiment agree within the limits of error with the theoretical values for transitions from vibrational levels with $K = 0$ or 2. (The theoretical value of $\eta = B(E2)_{2'\to 0}/B(E2)_{2'\to 2}$ is 0.7). If we calculate η using the data on relative intensities of γ rays in W^{184} as given in reference 9, we find that $\eta \approx 3$. This value of η would contradict the picture of the 900-kev level in W^{184} being a vibrational level. According to our data, $\eta \approx 0.7$ for W^{184}.

The closeness of the experimental values of η to the values computed theoretically for vibrational levels is a necessary but not a sufficient condition for identifying the tungsten levels which we are treating as vibrational levels. If we assume that these levels are single particle or "pair" levels, then since they are excited as a result of Coulomb interaction their spin must be 2 and their parity the same as that of the tungsten ground state. If in addition the quantum number K is 0 or 2 for these levels, the value of η will be the same as for transitions from β-vibrational or γ-vibrational levels, respectively.

From the data of reference 7 on the relative intensities of radiations emitted by W^{182} in transitions from the 1222-kev level to lower-lying levels of the rotational band based on the ground state of the W^{182} nucleus, it follows that this level has $K = 2$. Thus the 1222-kev level is not excited as the result of a pair transition (since we would then have to get a level with $K = 0$).

The energies of the excited levels of W^{184} and W^{186} considered in the present work are much lower than the level in W^{182}. It is known that in a heavy nucleus the energy of a level formed by a pair transition always exceeds 1 Mev. We should thus assume that the levels with $\Delta E = 900$ kev in W^{184} and 730 kev in W^{186} are also not "pair" levels.

For Coulomb excitation of a single particle level in an even-even nucleus, the value of K for the level must be 2 since the level has $I = 2$ and $K = I$

for single particle excitation. In this case the value of η will be the same as for γ-vibrational levels. Thus our experimental data on the ratio of the values of B(E2) generally speaking do not exclude the possibility that the highly excited levels of the tungsten isotopes which we are considering are the result of single particle transitions, and that these levels have K = 2, I = 2 and parity the same as that of the ground state.*

However there are arguments in favor of the assumption that these levels are γ-vibrational levels. The value J′ of the moment of inertia of the W^{182} nucleus in the excited state (ΔE = 1222 kev) is close to the value J for the ground state of this nucleus. (The values of the moments of inertia were determined from the energies of the two lowest levels in the corresponding rotational bands.) This result is to be expected for the case where the excitation is collective and the internal structure of the nucleus does not change. In single-particle excitation, the particle outside the closed shell has the familiar distorting effect on the nucleus, so in this case the value of the moment of inertia J′ of the nucleus in the excited state should be greater than the value J for the ground state.

Excitation of a single particle level in even-even nuclei must occur as a result of breaking up a pair of nucleons. In the nuclei we are considering, the pairing energy exceeds 1 Mev. Since the energies of the states excited in W^{184} (ΔE = 900 kev) and W^{186} (ΔE = 730 kev) are less than the energy of the state excited in W^{182} and also less than 1 Mev, if we assume that the level at ΔE = 1220 kev in W^{182} is not a single particle level we can also make the same assertion for these levels in W^{184} and W^{186}.

Reference 14 gives formulas for calculating the parameters B_2 and C_2 for γ-vibrational states:

$$\frac{B(E2)_{2'\to 0}}{e^2} = \frac{1}{5}\left(\frac{3}{4\pi} ZR_0^2\beta\right)^2 \frac{\hbar}{\sqrt{B_2C_2}}, \quad (1)$$

$$E_{\text{vibr.}} = \hbar\sqrt{C_2/B_2}. \quad (2)$$

Here Z is the atomic number of the nucleus, R_0 its radius, $E_{\text{vibr.}}$ the energy of the vibrational transition, and β the nuclear deformation parameter.

If on the basis of the arguments presented above we assume that these excited states are γ-vibrational states, we can use formulas (1) and (2) to compute the parameters B_2 and C_2 from the experimental values of B(E2) and $E_{2'\to 0}$ given in Table I.

The value of $E_{\text{vibr.}}$ was determined from the equation

$$E_{2'\to 0} = E_{\text{vibr.}} + \frac{\hbar^2}{2J}[I(I+1) - K^2],$$

where I = 2, K = 2.

In the computations we assumed that the moment of inertia J was equal to its value J_0 in the ground state. The results of the computations are shown in Table II.

TABLE II

Isotope	C_2, Mev	$\hbar^2/B_2$, Mev
W^{182}	21	0.023
W^{184}	18	0.042
W^{186}	14	0.10

In reference 14 the values of C_2 for vibrations in W^{182} and W^{186} were calculated using the eigenfunctions found by Nilsson.[15] These values are 24.5 and 27 Mev, respectively. In view of the experimental error in determining B(E2), the agreement between the values of C_2 given in Table II and the theoretical values must be considered to be satisfactory.

It is known that the energy of a rotational level with spin I is decreased by an amount ΔE_I as a result of interaction between rotational and vibrational excitation. Knowing the energies of the first and second rotational levels enables us to determine ΔE_I from the experiment. If we disregard the decrease in energy of rotational levels due to interaction with β vibrations, i.e., if we assume that ΔE_I is completely determined by the interaction between rotational and γ-vibrational excitations, we find from reference 14 that

$$\Delta E_I = -\frac{1}{6C_2}\left(\frac{\hbar^2}{J}\right)^2 I^2(I+1)^2,$$

Then using the values of ΔE_I and $\hbar^2/J$ found from experiment, we can determine C_2. For W^{182}, C_2 = 12.5 Mev. This calculation gives a lower limit for C_2.

Lack of precise data for the energy of the second rotational level of W^{184} and W^{186} prevents us from making similar calculations for these nuclei.

It is known that

$$B(E2)_{2'\to 0} = B(E2)_{2\to 0} E_{\text{vibr.}}/C_2. \quad (3)$$

For the tungsten isotopes $E_{\text{vibr}}/C_2 \approx 1/20$, while

*If the 2′ level has K = 2, the transition 2′ → 2 occurs with a change in K of two units. According to the selection rules given in reference 8, the M1 transition is forbidden in this case (K-forbiddenness), so that the 2′ → 2 transition will be mainly electric quadrupole.

$B(E2)_{2\to 0}$ is approximately 140 times as great as the reduced probability for a single particle transition. It follows from formula (3) that the ratio $F = B(E2)_{2'\to 0}/B(E2)_{s.p.}$ should be ~ 7. As we see from the values of F given in Table I, the value of F found from experiment actually is in this range.

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