an answer to our question in the shell model effects on the optical model parameters.

Lead

It appears that the proposed explanation of the behavior of the Pb^{208} cross sections in the neighborhood of 515 kev does indeed provide an excellent fit to the cross sections observed. While it may be debatable whether two levels of the same spin and parity can exist within their half-width and still be amenable to the usual resonance theory, there is no theoretical objection to the situation we observe in Pb^{208}. The $\frac{3}{2}^-$ level can certainly exist within the half-width of the $\frac{1}{2}^+$ level. It is true that the $\frac{1}{2}^+$ level required is unusually wide compared to the other resonances in Pb^{208}. However, in terms of the Wigner limit it is only about 5% of the single-particle width. For a double magic nucleus with very large spacing this is entirely possible.

ACKNOWLEDGMENT

The authors wish to acknowledge the generous help of the entire Van de Graaff group at Duke, and especially the cooperation and help of Dr. P. R. Bevington, Mr. R. J. Rummel, and Mr. W. Rolland in the development and design of this experiment. The support of the National Science Foundation under whose auspices some of the calculations were performed on the Duke University IBM-650 computer is also gratefully acknowledged. We also wish to thank Miss Dorothy Brand for help in numerous computations.

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Decay of 16-Minute Ta^{182m}†

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A revised decay scheme of the 16-minute isomer Ta^{182m} involves three states of Ta^{182} at excitation energies of 147 kev, 319 kev, and 503 kev. Transition multipolarities were classified by measuring both gamma-ray coincidences and internal conversion electrons. The 503-kev isomeric state decays mainly (98%) by a 184-kev $E3$ transition to the 319-kev state. This 319-kev state decays mainly (94%) to the 147-kev state by means of a 172-kev transition that is predominantly $M1$. The 147-kev transition to the ground state is also predominantly $M1$. Two of the three possible crossover transitions were observed; a 356-kev $M4$ transition originates at the isomeric level and a 319-kev $E2$ transition connects the second excited state with the ground state.

The 147-kev and the 319-kev states are probably the first and second excited rotational states of the ground-state configuration. The relevant rotational parameters are of particular interest because very little is known about moments of inertia for odd-odd nuclei.

The relative probabilities were determined for pile neutron activation of the 16-minute isomer, Ta^{182m}, and the 112-day ground state, Ta^{182}. If the ground-state formation cross section is taken as 21 barns, the corresponding value for the isomer is only 9 mb.

INTRODUCTION

The 16-minute Ta^{182m} activity was first reported by Seren, Friedlander, and Turkel,[1] who measured the slow-neutron activation cross section as 34±7 mb. The first preliminary energy measurement was made by Hole,[2] who assigned 180±7 kev to the isomeric transition after studying the conversion electrons in a magnetic spectrometer. The $E3$ classification[3] of the isomeric transition was based on the lifetime, the ratio of internal conversion coefficients,[2] and the K-shell conversion coefficient.[4]

We first re-examined the decay of 16-minute Ta^{182m} to search for a direct beta-decay branch to W^{182}, the daughter of the beta-decaying 112-day ground state, Ta^{182}. (No 16 minute beta branch was ever found. The experiments would have been quite sensitive to high-energy beta rays from Ta^{182m} to levels near the ground state of W^{182}, but it is difficult to estimate the sensitivity to low-energy beta rays.)

During these measurements, our coincidence scintillation studies uncovered two cascade gamma rays with

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* Summer Visitor at Brookhaven National Laboratory, Upton, New York, when this work was begun.

[1] L. Seren, H. N. Friedlander, and S. H. Turkel, Phys. Rev. **72**, 888 (1947).

[2] N. Hole, Ark. Mat. Astron. Fysik **36A**, No. 9 (1948).

[3] M. Goldhaber and A. W. Sunyar, Phys. Rev. **83**, 906 (1951).

[4] A. W. Sunyar, Phys. Rev. **83**, 864 (1951).

TABLE I. Internal conversion electrons.

γ ray	Observed conversion lines	Averaged energy sum (kev)	Comment[a]
147	K, L, M	147.4 ± 0.5	High K/L
172	K, L	172.0 ± 1.5	High K/L
184	K, L, M	184.3 ± 1.5	Dominant L conversion. K/L ratio low
319	...	$319\ \pm3$	Scintillation counter measurement. No conversion lines seen
356	K, L	$354\ \pm3$	Very weak lines
100	L, M	99.8 ± 0.5	Long-lived Ta^{182}

[a] Source thickness effects preclude any multipolarity statements based on L-subshell conversion ratios.

energies about 150 kev and 170 kev together with a 320-kev cross-over gamma ray.[5] The preliminary internal conversion spectrum was not good enough to identify the isomer.

This paper reports improved coincidence scintillation studies and an improved internal conversion electron spectrum which together uniquely identify three excited states and five gamma-ray transitions. A discussion of the possible interpretations of the rotational nature of the first two excited states will follow the presentation of the experimental results.

EXPERIMENTAL PROCEDURE

The gamma-ray detectors were 3-in.×3-in. NaI(Tl) scintillators mounted on Dumont-6363 photomultipliers. A standard fast-slow coincidence system ($\tau_{\text{fast}}=10^{-7}$ sec) was used to provide a gating signal for a 100-channel pulse-height analyzer which recorded the coincidence gamma-ray spectrum from one scintillation crystal. This fast-slow coincidence system required that the pulse from the other scintillation detector fall within an adjustable energy range. In the triple coincidence measurements, energy requirements were placed on both scintillation detectors whose pulses were not displayed. Spurious coincidences due to scattering were minimized by using graded absorbers (Pb, Cd, and Cu) between the detectors.

The internal conversion electron spectrum was obtained with a film-recording 180° permanent magnet spectrograph whose field was 269 gauss. Due to the small activation cross section it was necessary to use a relatively thick sample (12 mg/cm^2) and to activate it repeatedly. The sample was irradiated for 15 minutes, inserted into the spectrograph about 1 minute after the irradiation, and allowed to remain there for 30 minutes. In order to obtain sufficient density on a single film, this cycle was repeated 12 times using two samples; the sample change after 6 cycles was desirable because the 112-day Ta^{182} was becoming too intense. The source was inserted into the spectrograph through a vacuum lock.

EXPERIMENTAL RESULTS

A. Intensity Measurements and Coincidences

The internal conversion electron spectrum is shown in Fig. 1, and the data are given in Table I. The large source thickness limited the precision of both the energy and the relative electron intensity determinations. From Fig. 1, one can identify the 184-kev transition as an isomeric transition because it has both a relatively large total internal conversion and a relatively small K/L conversion ratio. (This low value of K/L cannot be attributed to source thickness inasmuch as both the 147-kev and the 172-kev transitions have high K/L ratios.) The low K/L ratio further implies that the 184-kev isomeric transition is an electric multipole rather than a magnetic multipole.

The pulse-height distribution from the 16-min Ta^{182m} gamma rays, as detected by a 3-in.×3-in. NaI(Tl) scintillator, is shown by the open circles in Fig. 2. Because the source was 8 in. from the detector, there is very little distortion due to summing in the detector. The relative intensities of the gamma rays emitted by the 16-minute isomer are given in Table II; slight corrections have been made for summing.

The 319 ± 3 kev gamma ray has the correct energy to be the cross-over transition in parallel with the 172-kev +147-kev cascade. Similarly, the 354 ± 3 kev gamma ray (whose energy was determined from weak internal conversion electrons as indicated in Table I) could be the possible 356-kev cross-over gamma ray in parallel with the 184-kev+172-kev cascade.

The relative internal conversion coefficients implied by the data of Tables I and II indicate that the multipolarity of the 356-kev transition is higher than that of the 319-kev transition. The 356-kev transition has fewer photons by a factor of 15, whereas the 319-kev transition had too few conversion electrons to be recorded on the spectrogram of Fig. 1. Additional evidence for the high multipolarity of the 356-kev transition is its low K/L conversion ratio, which can be estimated visually as about 2 or 3.

Figure 3 shows four different coincidence spectra obtained by setting different energy requirements on the radiations of the scintillator whose spectrum was not displayed. In all cases, the source was close enough to each of the two 3-in.×3-in. detectors to give sum peaks at 319 kev (147+172), 331 kev (147+184), and 356 kev (172+184). These sum peaks dominate over the actual 319-kev and 356-kev photon transitions. The 112-day background has not been subtracted in Fig. 3, but this does not affect the main features of the data. These four coincidence spectra show clearly that photon coincidences exist involving x rays and three different photon groups with energies between 147 kev and 184 kev. Curve A shows that K x ray coincidences with the

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[5] P. Axel and A. W. Sunyar, *Proceedings of the Glasgow Conference on Nuclear and Meson Physics* (Pergamon Press, New York, 1954), p. 195.

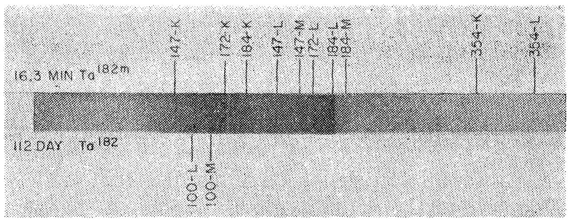

FIG. 1. Internal conversion electron spectrum of Ta^{182m}.

TABLE II. Relative photon intensities.

γ ray	Relative intensity
K	0.83
(147+172+184)	1.00
147	0.383
(172+184)	0.617
172	0.40
184	0.217
319	0.053
356	0.0033

147-kev photons are less likely than K x ray coincidences with the unresolved 172-kev+184-kev composite; this implies either a high K-conversion coefficient of the 147-kev transition or a low K-conversion coefficient for one of the other two transitions. Curves B, C, and D show that there are indeed photons of three different energies between 147 kev and 184 kev. Curve B is mainly a composite of the 172-kev and 184-kev photon groups, because the energy selection on the nondisplayed detector was set to accept mainly 147-kev photons. Similarly, the energy selection for curve C favored the 172-kev photons most, but also included some 184-kev photons. For curve D, the 184-kev photon was selected in the nondisplayed counter, and the coincidence curve shown is mainly a composite of the 147-kev and 172-kev photons.

The final decay scheme shown in Fig. 4 is completely consistent with the intensity data (Tables I and II) and the coincidence measurements (Fig. 3). The branching ratios given in Fig. 4 were based on the additional internal conversion coefficient measurements described below.

B. Internal Conversion Coefficients

The conversion electron spectrum of Fig. 1 was used to obtain approximate K/L conversion ratios for the 147-kev, 172-kev, 184-kev, and 356-kev transitions as indicated in Table III. Inasmuch as no attempt was made to correct accurately for source thickness effects, these ratios are only semiquantitative. However, together with the conversion coefficients, these values are adequate to provide multipolarity assignments.

The absolute K-shell internal conversion coefficient was measured rather directly for both the 147-kev and the 184-kev transitions; the conversion coefficients for both the 172-kev and 356-kev transitions were obtained somewhat indirectly by making use of the measured values for 147-kev and 184-kev transitions. The experimental determinations of the conversion coefficients listed in Table III are described briefly in the following paragraphs. The theoretical values of the internal conversion coefficients[6] are also shown in Table III.

The K-shell internal conversion coefficient of the 147-kev transition was determined by comparing the intensities of the 147-kev photons and of those Ta K x rays which originated due to the K-shell conversion of the 147-kev transitions. These events, associated with the 147-kev transition, were isolated by requiring a triple coincidence in which each of the two auxiliary detectors selected events on the high-energy side of the 172-kev and 184-kev composite peak. The coincidence spectrum is shown in Fig. 5. These data, after corrections are made for detection efficiency and x-ray fluorescence yield ($f_K=0.94$) give a 147-kev K-shell conversion coefficient equal to 1.0±0.15. The 147-kev internal conversion measurements favor an $M1$ assignment but an $E1+M2$ mixture cannot be ruled out without the aid of lifetime measurements discussed below.

Photon and x-ray intensities were also compared in order to measure the 184-kev K-shell conversion coefficient. In this case, a double coincidence arrangement was used; the energy selected on the undisplayed

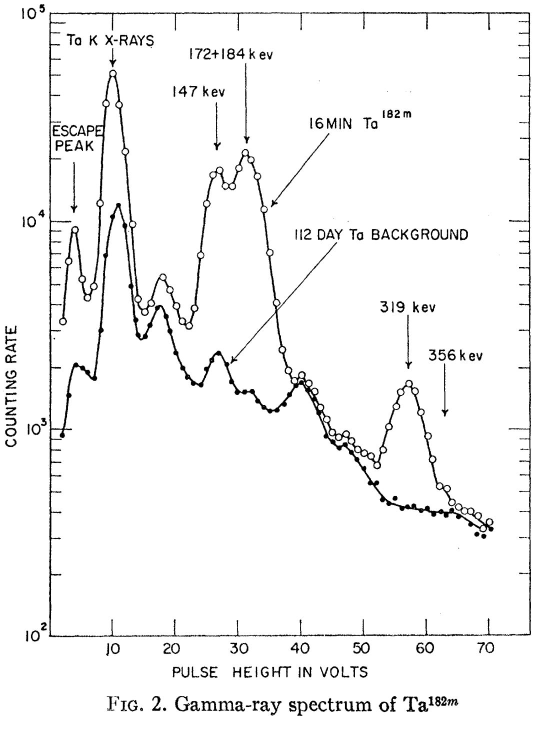

FIG. 2. Gamma-ray spectrum of Ta^{182m}

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[6] M. E. Rose, *Internal Conversion Coefficients* (North-Holland Publishing Company, Amsterdam, 1958); L. A. Sliv and I. M. Band, Leningrad Physico-Technical Institute Reports, Part I, 1956 and Part II, 1958 [translation: University of Illinois Reports 57-ICC-K1 and 58-ICC-L1, respectively].

detector was 319 kev. In the coincidence geometry, this energy selection emphasized 319-kev gamma rays and sum events of 147 kev+172 kev. However, included in the selected energy range are other sum events composed of either 172-kev and 184-kev photons, or 147-kev and 184-kev photons. The coincidence spectrum is shown in Fig. 6. The 147-kev peak in Fig. 6 is due to the sum event caused by the simultaneous detection of 172-kev and 184-kev photons by the auxiliary detector. The dashed curve in Fig. 6 is an estimate of the 147-kev transition contribution based on the observed 147-kev photon peak in Fig. 6 and the corresponding K x rays implied by Fig. 5. It is not possible to correct for 172-kev transitions which contribute to the curve in Fig. 6 due to the summing of 147-kev and 184-kev photons in the auxiliary detector. However, this does not introduce a significant error because independent measurements, described below, indicate that the 172-kev K-shell conversion coefficient is about the same as that of the 184-kev transition. The value of the 184-kev K-shell conversion coefficient is 0.74 ± 0.15. As shown by Table III, this implies that the 184-kev transition is $E3$. This was further checked with a coincidence experiment involving better geometry, with 5.5 inches between the source and the scintillator whose spectrum was displayed. The photons in coincidence with K x rays are shown in Fig. 7; this spectrum is similar to that shown in Fig. 3(A) except that the improved geometry greatly attenuates the summing which otherwise dominates the 319-kev to 356-kev energy region. In the coincidence spectrum of Fig. 7, the 319-kev to 356-kev photon ratio is 4.7 ± 1; the corresponding ratio in the singles spectrum (Fig. 2) is 16 ± 4. This relative enhancement of

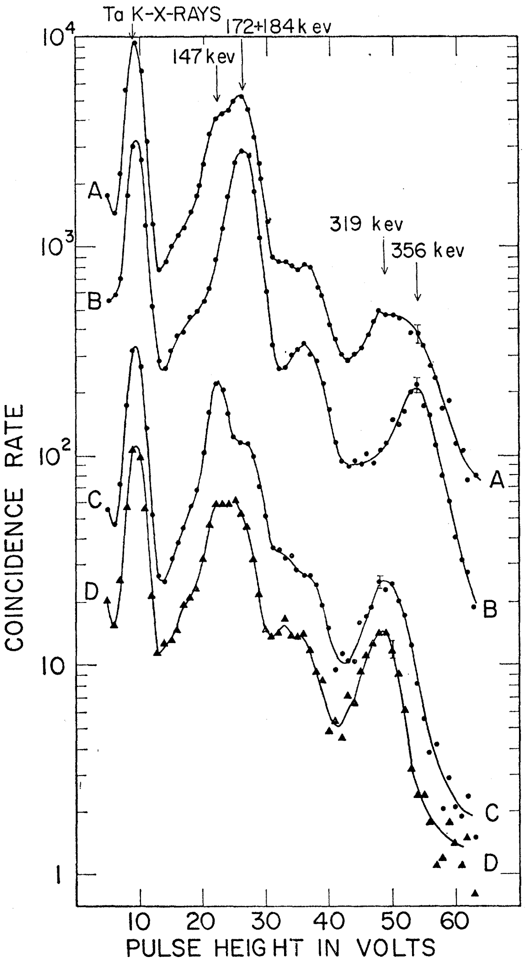

FIG. 3. Coincidence spectra arising from decay of Ta^{182m}. Curve A: Coincidence gate on K x rays. Curve B: Coincidence gate on 147-kev photopeak. Curve C: Coincidence gate on peak of (172+184)-kev photopeak. Curve D: Coincidence gate on high side of (172+184)-kev photopeak.

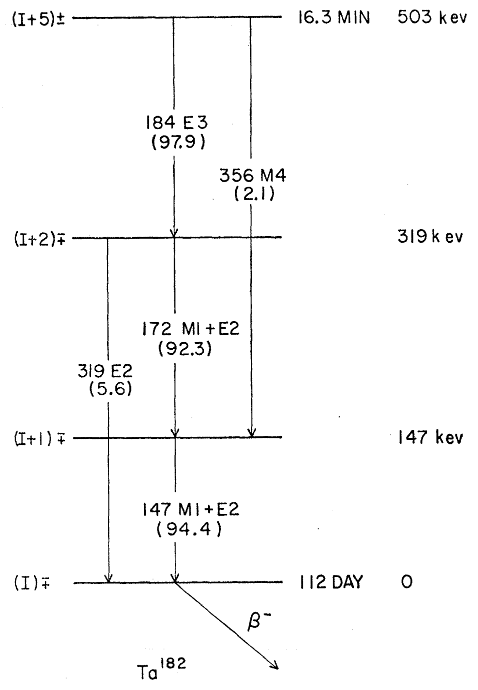

FIG. 4. Disintegration scheme of Ta^{182m}.

TABLE III. Internal conversion coefficients.

Energy (kev)	Quantity	Experimental value	Theoretical values	
147.4	(N_{ek}/N_γ)	1.0 ± 0.15	$M1$—1.23	$E2$—0.39
147.4	K/L	$\gg1$	$M1$—6.1	$E2$—1.0
172	$N_{ek}/(N_\gamma+N_{ek}+N_{eL})$	0.34^a	$M1$—0.37	$E2$—0.16
172	N_{ek}/N_γ	0.75 ± 0.3^a	$M1$—0.78	$E2$—0.25
172	K/L	$\gg1$	$M1$—6.5	$E2$—1.3
184.3	N_{ek}/N_γ	0.74 ± 0.15	$E3$—0.61	
184.3	K/L	<1	$E3$—0.3	
319	N_{ek}/N_γ	<0.1	$E2$—0.049	
356	N_{ek}/N_γ	~4	$M4$—3.0	
356	K/L	~2.5	$M4$—2.1	

[a] Based on decay scheme as indicated in text.

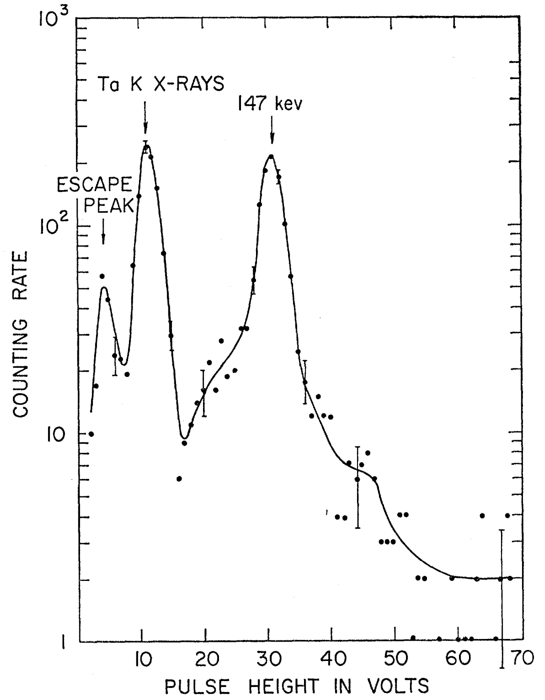

FIG. 5. Spectrum of gamma rays recorded by a 3-in.×3-in. NaI(Tl) scintillation counter in triple coincidence with two detectors whose energy selecting channels were both placed on the high side of the (172+184)-kev photopeak.

356-kev photons by a factor of 3.4±1.1 is a measure of the ratio of *K* x rays associated with the 147-kev and 184-kev transitions, respectively. This enhancement ratio of 3.4 is consistent with the measured *K*-shell conversion of the 147-kev transition and an *E*3 assignment of the 184-kev transition. The main difference between the 147-kev and 184-kev transitions is that the 184-kev transition is dominated by *L*-shell conversion; the *K*-shell conversion coefficients of these transitions are rather similar although there is a large difference in the total conversion.

It is possible to obtain reliable estimates of the *K*-conversion coefficient of the 172-kev transition despite the fact that the poor energy resolution precludes the possibility of using coincidence techniques directly. One such estimate is obtained by combining relative electron intensity data with the measured conversion coefficients and the decay scheme. From the spectrogram shown in Fig. 1, the *K*-electron intensity of the 172-kev transition can be estimated as twice that of the 184-kev transition. If the 184-kev transition is accepted as *E*3, this electron ratio implies that there are 34 *K*-holes produced by the 172-kev transition per 100 decays of the isomeric state. As shown in Table III, this strongly favors an *M*1 assignment of the 172-kev transition; the *M*1 prediction would be about 37 *K*-holes per 100 isomeric decays. Another check on the multipolarity of the 172-kev transition can be obtained by using the other measured data to deduce the number of *K* x rays and photons contributed by the 172-kev transition to the singles spectrum of Fig. 2. This indirect method depends on the measured 147-kev *K*-shell conversion and the theoretical prediction for the 184-kev *E*3 conversion coefficients; the actual calculation also takes into account the 319-kev and 356-kev transitions, but these weak branches have little importance. This method gives the value of 0.75±0.3 for the 172-kev *K*-shell conversion coefficient; it also gives a value of about 1 for the total conversion coefficient. The *M*1 multipolarity of the 172-kev transition is further confirmed by the spin and parity changes implied by other transitions between the isomeric level (503 kev) and the levels at 319 kev and 147 kev. The identification of the 184-kev transition as *E*3 implies that the levels at 319 kev and 503 kev differ in spin by 3 units and have different parity; the assignment (to be made below) of *M*4 multipolarity to the 356-kev transition implies that the levels at 147 kev and 503 kev differ in spin by 4 units and have different parity. These identifications show that the 172-kev transition from the 319-kev level to the 148-kev level should have an *M*1 multipolarity.

The possible multipolarity assignment of the 319-kev transition can be restricted to either *E*2 or *E*1 because its conversion electron lines were too weak to be seen. *K*-shell conversion electrons of the 319-kev transition would surely have been detectable if they had been 1/2 as numerous as the observed *K*-shell electrons of the 356-kev transition. Since there are 16 times as many 319-kev gamma rays as 356-kev gamma rays, the 319-kev *K*-shell conversion must be less than 1/32 of the 356-kev *K*-shell conversion coefficient. This implies a 319-kev *K*-shell conversion coefficient of less than 0.1 if the theoretical 356-kev *K*-shell conversion is used. The *E*1 assignment can be ruled out if, as is strongly indicated below, the 147-kev transition involves no parity change (i.e., if the 147-kev multipolarity is either *M*1 or a mixture of *M*1 and *E*2).

The multipolarity of the 356-kev transition can be identified as *M*4 with the aid of the conversion measurements even though these measurements were quite crude. The *K*-shell conversion coefficient was measured by estimating the intensity of the 356-kev *K*-shell electrons relative to the 184-kev *L*-shell conversion. This ratio, which could be estimated to within a factor of 2, implied that there were about 1.5 356-kev *K* electrons per 100 isomeric transitions. The gamma-ray intensity measurements implied about 0.35 unconverted 356-kev photons per 100 isomeric transitions. The resultant *K*-shell conversion coefficient of about 4 definitely excludes electric multipoles and favors an *M*4 assignment. Similarly, the measured *K*/*L* ratio of about 2.5 favors the *M*4 assignment. The *M*4 assignment becomes even more definite if one estimates the expected lifetime for *M*3, *M*4, and *M*5 transitions.

C. Lifetime Measurements and Comparisons

The 16.3-minute half-life of the isomeric state together with the measured branching ratios imply a partial half-life for 356-kev gamma-ray emission of 2.8×10^5 seconds. This value is most consistent with the single-particle proton estimate for $M4$, which is 4.7×10^3 seconds; $M3$ would give 1.1×10^{-2} second, whereas $M5$ would give 3.3×10^9 seconds.[7] The 356-kev transition is slow by a factor of about 60 compared with the single particle estimates. Although slow isomeric transitions are usual, the factor of 60 is about a factor of 10 larger than usual for an $M4$ transition.[8] This extra factor of 10 may be due to K forbiddenness[9]; the most likely spin values imply that $\Delta K=5$ which is forbidden for a $\Delta I=4$ transition.

The partial half-life of the 184-kev gamma-ray transition is about 4×10^3 seconds. This is slower, by a factor of 5×10^4, than the $E3$ single-particle proton estimate of 8.5×10^{-2} second.[7] Some other very slow $E3$ transitions are known, but, once again a K-selection rule may be inhibiting the decay.[9]

A careful search was made for any possible delay in the emission of the 147-kev gamma ray using an overlap type coincidence analyzer.[10] An upper limit of $\sim10^{-9}$ second can be set on the mean life of the 147-kev state. This measurement can be used as a strong argument against the possibility that the 147-kev transition is a mixture of $E1$ and $M2$. This $E1+M2$ possibility cannot be discarded solely on the basis of conversion coefficients because as little as a 10% mixture of $M2$ with 90% $E1$ could give the measured 147-kev K-shell conversion. If there was a 10% $M2$ branch, the upper limit of its partial half-life for gamma-ray decay would be about 1.3×10^{-8} second. The single-particle proton estimate for this transition would be about 3.7×10^{-6} second. Therefore, if the 147-kev gamma ray were an $E1$ and $M2$ mixture, the $M2$ would have to be faster than the single particle estimate by a factor of about 300. Inasmuch as no $M2$ transitions are known to be even as fast as the single-particle estimate, the $E1$ and $M2$ mixture seems quite unlikely. This implies that the 147-kev transition must be $M1$ or an $M1+E2$ mixture, and that the ground state and the 147-kev state have the same parity. This assignment implies further that the 319-kev gamma ray is an $E2$ transition.

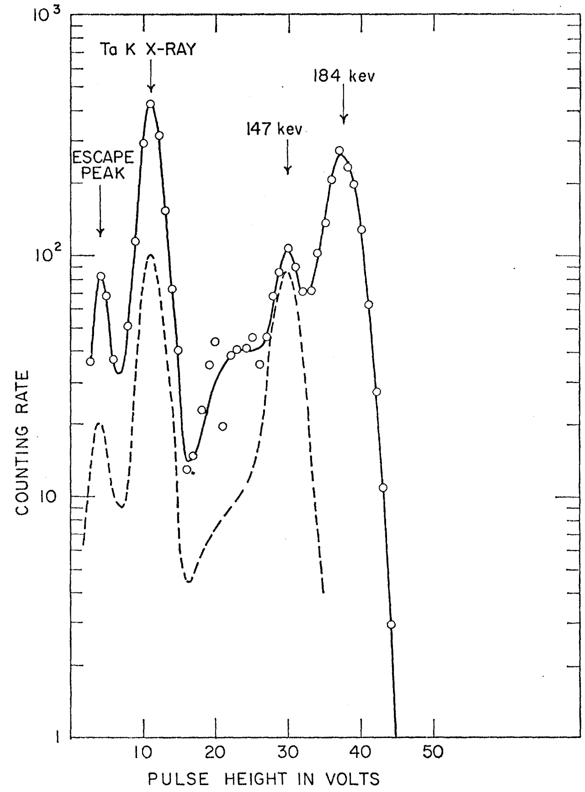

FIG. 6. Spectrum of gamma rays recorded by a 3-in.×3-in. NaI(Tl) scintillation counter in coincidence with a detector whose energy selecting channel was placed on the 319-kev photopeak.

D. Slow Neutron Activation Cross Section

The activation cross section of the 16-minute isomer by (Brookhaven) pile neutrons was compared with that of the 112-day ground state. In one measurement, the unconverted 100-kev photons associated with the ground-state decay were compared with the 16-minute K x rays. Corrections were applied for the activation period in the reactor and the counting interval during which the measurements were made. The fraction of the ground-state decays leading to the unconverted 100-kev photons was taken as 0.142[11]; the number of K x rays per isomeric decay was taken as 0.88 based on our measurements and decay scheme. These data indicated that the ground-state activation is favored over the isomeric state activation by a factor of about 2300±580. Strictly speaking, this ratio is for the neutron energy distribution in the Brookhaven reactor. If 21 barns is accepted as the activation cross section of the 112-day Ta^{182} ground state, the activation cross section for 16-minute Ta^{182m} is $(9.1\pm2.3)\times10^{-3}$ barn. This measurement was checked semiquantititively by comparing the 147-kev K-shell conversion electrons with the L-shell conversion electrons of the 100-kev transition. It

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[7] S. A. Moszkowski, Phys. Rev. **83**, 1071 (1951); V. F. Weisskopf, Phys. Rev. **83**, 1073 (1951). We use the single particle proton estimates, and a nuclear radius equal to $R=1.2\times10^{-13}A^{\frac{1}{3}}$, following reference 8. The S factor is set equal to 1.

[8] M. Goldhaber and J. Weneser, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Palo Alto, California, 1956), Vol. 5, p. 1.

[9] G. Alaga, K. Alder, A. Bohr, and B. Mottelson, Kgl. Danske, Videnskab. Selskab, Mat.-fys. Medd **29**, No. 9 (1955).

[10] A. W. Sunyar, *Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958* (United Nations, Geneva, 1958), Vol. 14, p. 347.

[11] Numerous references to gamma-ray intensity measurements on Ta^{182} are tabulated by D. Strominger, J. M. Hollander, and G. T. Seaborg, Revs. Modern Phys. **30**, 585 (1958).

is not surprising that our cross-section value differs from the value of 34×10^{-3} barn which was derived from an electron detection system interpreted with an inadequate decay scheme.[1]

The strong favoring of the ground state of Ta^{182} in slow neutron activation implies that its spin is relatively close to the 7/2 spin[12] of Ta^{181}, while the spin of 16-minute Ta^{182m} must be quite different.[13] Although many cases are known in which isomers of unfavored spin have only from 0.01 to 0.1 of the total activation cross section,[13] ratios as small as 1/2300 are extremely rare and probably imply an exceptionally large spin change.

INTERPRETATION USING COLLECTIVE MODEL

Ta^{182} is probably a nonspherical nucleus, and might therefore have low-lying states which are rotational excitations of the ground state.[14] The 147-kev and 319-kev levels populated in the Ta^{182m} decay can be interpreted as these expected rotational states. If this interpretation is accepted, collective model parameters, such as the moment of inertia and the magnetic moment, can be defined for the odd-odd Ta^{182} nucleus. Inasmuch as these parameters depend on the spin of the ground state of Ta^{182}, evidence from other sources about its spin is given below before the collective parameters are discussed.

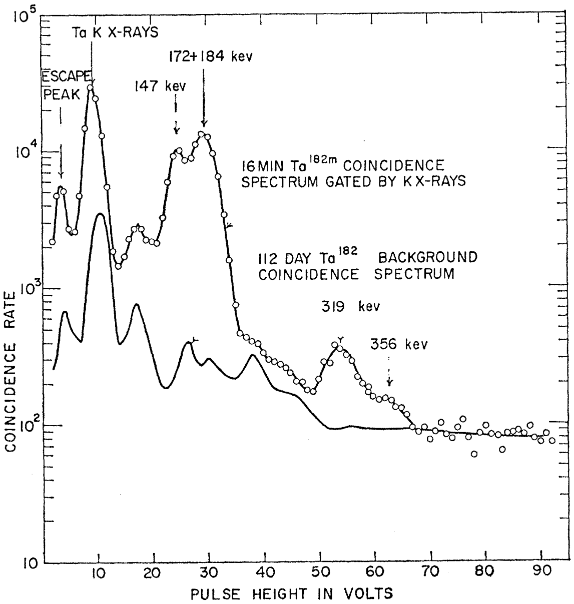

FIG. 7. Spectrum of gamma rays recorded by a 3-in.×3-in. NaI(Tl) scintillation counter in coincidence with a detector whose energy selecting channel was placed on the Ta *K* x ray photopeak. Source located at $5\frac{1}{2}$ in. from counter face to reduce summing.

Evidence About the Spin of 112-Day Ta^{182}

One might hope to infer the spin and parity of the 112-day ground state of Ta^{182} from its radioactive decay. Additional information about Ta^{182} and its excited states can be obtained from the gamma rays following neutron capture in Ta^{181}. Unfortunately, neither type of evidence leads to a unique spin assignment; in fact, the evidence from these two sources appears contradictory. The radioactive decay seems to favor a spin of 3 (or 4), whereas the capture gamma-ray data seem to imply a higher spin.

The radioactive decays of both 112-day Ta^{182} and 60-hour Re^{182} have led to the identification of many energy levels in W^{182}. However, the beta-ray decay branching of Ta^{182} to these established levels in W^{182} is not certain enough to define the spin of Ta^{182}. Early measurements[15] had not been precise enough to lead to the complex level diagram of W^{182}. After the DuMond crystal focussing gamma-ray spectrometer supplied the necessary precision,[16] each of several different auxiliary measurements suggested the main features of the decay scheme. Fowler *et al.*[17] measured the energies of the gamma rays somewhat above 1 Mev; their proposed decay scheme was aided by the systematics of even-even nuclei presented by Scharff-Goldhaber.[18] Mihelich used coincidence measurements[19] and the reported 10^{-9} second half-life[20] in W^{182} to choose among the alternative decay schemes.[16] Boehm, Marmier, and DuMond[21] used their conversion electron measurements together with the reported coincidence measurements[19] to establish the essential features of the currently accepted decay scheme. At this stage, the energy levels in W^{182} were interpreted[9] in terms of the Bohr-Mottelson collective model.[14]

Despite the considerable additional information which has become available more recently, the beta-ray branching of Ta^{182} remains in doubt. In the most complete report of the 112-day Ta^{182} decay, Murray *et al.*[22] give only a qualitative indication of the beta branching. Many of their energy and spin assignments for W^{182}

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TABLE IV. Energies and absolute intensities of low-energy capture gamma rays ($Ta^{181}+n$).

	(a)		(b)	(c)	
Dominant gamma ray kev	Nearby weaker gamma rays kev	Nominal energy kev	Intensity per captured neutron	Nominal energy kev	Intensity per captured neutron
112	120, 109, 106, 103, 101	107	0.15	107	0.09
133	141, 138, 126, 123	133	0.30	133	
171	192, 164	170	0.22	175	0.16
268	293	272	0.70	280	0.39
402	408, 416	···	···	405	0.20

[a] Reference 30.
[b] Reference 33.
[c] Reference 34.

levels have been confirmed by precision high-energy gamma-ray measurements,[23] detailed coincidence studies,[24] and angular correlation experiments.[25] Significant additional confirmation of the levels in W^{182} came from the complete investigation made by Gallagher and Rasmussen[26] of the 60-hour Re^{182} decay. (This most recent report on W^{182} levels changed one energy and one spin assignment but did not affect the Ta^{182} beta branching interpretation directly.) There is some disagreement about gamma-ray intensities[22,24,27] which casts doubt on any beta-ray branching ratios inferred from gamma-ray intensities. The direct measurement of beta-ray branches is impeded by the numerous conversion electron lines.[17,22] The only published values of beta branching ratios[28] disagree both with those implied by the complete decay scheme[22] and with coincidence measurements[20,24] (if the highest energy Ta^{182} beta ray leads to the 2+ state, D,[22,26] at 1222 kev in W^{182}). A final serious complication in interpreting this beta decay is the unknown role of model-dependent selection rules; K forbiddenness[9] and intrinsic state changes[29] may govern the beta branching.

Although the uncertainties listed above preclude a definite Ta^{182} spin-parity assignment from currently available beta-decay evidence, some tentative assignments are possible. There seems to be appreciable branching both to a presumed 2− level (state $F^{22,26}$) and to a presumed 4− level (state $K^{22,26}$). (The log ft for these transitions depends on the uncertain branching ratios but is about 8.3.) Should the branching to 2− and 4− levels be confirmed, a spin assignment of 3 for Ta^{182} might be favored, although neither 2 nor 4 could be excluded without knowing which selection rules were governing. (These selection rules would also be needed to determine the parity.) If beta branching to spin 2 states were found to be small, a spin assignment of 4 might be preferable; if there were no beta branching to spin 2 states, the Ta^{182} spin might be 5.

The information from neutron capture gamma-ray spectra is also difficult to interpret but both the high- and low-energy data would be easier to understand if the Ta^{182} ground-state spin were 4 or 5. A gamma ray of 6.060±0.008 Mev has been reported,[30,31] which probably goes to the ground state of Ta^{182} in about 0.5% of the neutron capture events.[31] [No gamma rays with energies above 6.06 Mev have been seen even though a gamma ray 5% as intense could have been detected[30]; furthermore, the neutron binding energy deduced from the $Ta^{181}(d,p)$ reaction is 6.03±0.15 Mev[32]]. The other high-energy gamma rays which have been identified[30,31] must terminate in excited energy levels in Ta^{182}. The available data with the best resolution[30] imply six states of Ta^{182} within the first 600 kev; the energies are within about ±8 kev of: 99 kev, 278 kev, 368 kev, 485 kev, 517 kev, and 572 kev. The intensities of the seven relevant high-energy gamma rays are of the same order of magnitude; the most intense is the 5.961-Mev gamma ray[30] which leads to the "99-kev" state in about 1% of the neutron capture events.[31] There is no evidence for high-energy gamma rays leading to either the 147 kev or the 319-kev states reported in this paper. (Particular care was undoubtedly taken in searching for a high-energy gamma ray terminating at about 180 kev because it was thought to be the isomeric level in Ta^{182}.) From the published gamma-ray spectra, one can estimate crudely that the 5.913-Mev or 5.741-Mev gamma rays to these states would have been noticed if either had 1/6 the intensity of the 5.961-Mev gamma ray.

Many low-energy capture gamma rays have also been observed. In their list of the more intense gamma rays with energies between 91 kev and 509 kev, Bartholomew *et al.*[30] list 31 gamma rays. Twenty-one of these have been fitted into a very tentative decay scheme which involves eleven excited states up to 821 kev in energy, including eight levels that are consistent with the highest energy gamma rays.[30] Within 5 kev of the gamma-ray energies we observe in the 16-minute decay, there are capture gamma rays at 145 kev, 152 kev, 171 kev, and 357 kev (the 145 kev and 152 kev are

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TABLE V. Rotational parameters for Ta^{182}.

Parameter	Value calculated for different ground state spins			Comment
	$I=3$	$I=4$	$I=5$	
$(E_2-E_1)/(E_1-E_0)$	1.25	1.20	1.17	Experimental: 1.17±0.01
E_3 (kev)	534	527	523	Calculated assuming pure rotational excitation
$3\hbar^2/\mathcal{I}$ (kev)	110	88	74	Less than 100 kev expected
$g_\Omega-g_R$	±1.5	±0.97	±0.69	Assuming $Q=7\times10^{-24}$ cm^2
g_Ω	$+1.8$ or -1.2	$+1.3$ or -0.7	$+1.0$ or -0.4	If $g_R=0.3$
μ	3.8 or -2.9	4.4 or -2.5	4.4 or -1.4	
$(M_1\text{ photons}/E_2\text{ photons})_{147}$	22	35	51	
$(M_1\text{ photons}/E_2\text{ photons})_{172}$	19	30	44	

known to ±2 kev whereas 171.0±0.2 kev and 356.8±0.3 kev are quoted[30]). However, the 171-kev and 357-kev capture gamma rays are not those participating in the 16-minute Ta^{182} decay because other related 16-minute gamma rays do not appear in sufficient intensity in the capture gamma-ray spectrum. In particular, the 145-kev gamma ray observed in the capture spectrum is too weak.[30] Of course, the 319-kev and 147-kev states might be excited slightly but the main gamma-ray cascades to the ground state do not involve these excited states. The very small neutron activation cross section for the 503-kev 16-minute isomeric level in Ta^{182} makes it clear that gamma rays from this isomeric level would not appear in significant intensity during a capture gamma-ray experiment.

The absolute intensity of the strongest low-energy gamma rays have been measured using poor energy resolution.[33,34] The reported intensities per captured neutron are shown in Table IV together with the energy assignment implied by higher resolution measurements.[30] The high absolute probability of finding these gamma rays is sometimes taken as evidence that they originate at low-lying levels of Ta^{182} from which competing higher energy dipole gamma rays cannot be emitted.

Although the interpretations of the high-energy and low-energy portions of the capture gamma-ray spectrum may be different, both favor a Ta^{182} ground-state spin assignment of greater than 3. The multipolarities of the gamma rays we observe fixes the spins of 147-kev and 319-kev levels as $I+1$ and $I+2$ if the ground state spin is I. ($I-1$ and $I-2$ would be acceptable only if I were 5 or greater.) The parities of these three levels is the same. The compound system formed by the capture of an s neutron by Ta^{181} has a spin of $7/2\pm1/2$. One would expect to see the unobserved 5.913-Mev gamma ray to the 147-kev level if the ground-state spin of Ta^{182} were 3. Even if the 6.060-Mev ground-state gamma ray is a direct transition,[35] the 5.913-Mev gamma ray would be expected to compete effectively, particularly if the 147-kev state has the same intrinsic configuration of the ground state. If the 6.060-Mev gamma ray originates in compound nuclear states of spin 3 or 4 (or both 3 and 4) rather than in a direct transition, these compound states are probably highly mixed configurations, and only the spins and parities of the ground state and 147-kev level should influence the high-energy gamma-ray transitions.

Similar, but even stronger arguments favoring a Ta^{182} ground-state spin of at least 4 or 5 can be based on the low-energy gamma-ray spectrum. After the emission of the first few gamma rays in the capture gamma-ray cascade, the population of different spins must be distributed over a variety of spin values (more or less centered at 3 or 4). Furthermore, the states populated just before the final gamma ray is emitted would be expected to have a wide variety of nuclear configurations. If the observed intense low-energy capture gamma rays do not originate at very low-lying levels, a high ground-state spin (and a higher 147-kev spin) would be required to explain why so few transitions reach the 147-kev excited state. Even if the strong low-energy transitions do originate at low-lying excited states, a high spin for the 147-kev level would be needed to explain why it did not compete successfully with these low-lying states for the gamma-ray cascades.

Collective Parameters for Ta^{182}

If the 147-kev and 319-kev levels are assumed to be the first and second rotational excitations of the ground state, it is possible to predict (1) the energy of the third rotational level, (2) the moment of inertia, (3) the magnetic g factor, (4) the magnetic moment, and (5) the $E2$ admixtures in the $M1$ transitions. Inasmuch as each of these parameters depends on the uncertain ground-state spin of Ta^{182}, Table V lists the values of these parameters for three different I values, from $I=3$ to $I=5$.

(1) *Energy*. According to the collective model,[14] the first excited rotational state would have a spin $I_1=I+1$ (at an energy of E_1); the second rotational excitation, at E_2, would have a spin $I_2=I+2$. (I and E_0 are taken as the spin and energy of the ground state.) For pure rotational excitation, the unique prediction for the

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energy ratio is: $(E_2-E_1)/(E_1-E_0)=(I+2)/(I+1)$. The values given in Table V show that if the 147-kev and 319-kev levels were pure rotational levels, the Ta^{182} ground-state spin would be $I=5$. However, the rotational spectrum may be disturbed due to either rotation-vibration coupling[14] or to rotation-particle coupling.[36] The deviation from pure rotational coupling for the $I=3$ assignment is in the direction expected for rotation-vibration coupling, but the deviation is relatively large.[37] On the other hand, the rotation-particle interaction is expected to distort the rotational spectrum in an odd-odd nucleus, such as Ta^{182}, in which many states are expected at low excitation. (For example, the low-lying levels implied by the neutron capture data might have spins which could couple with and distort the rotational excited states.) The energy of the third excited rotational state can be predicted accurately either if there are pure rotational levels or if the impurity were analyzed in detail. In Table V, we list $E_3=E_2+(E_2-E_1)(I+3)/(I+2)$.

(2) *Moment of Inertia.* One of the most interesting parameters of the collective model is the moment of inertia, $\mathcal{I}$, which can be inferred from the rotational energy spacing. Table V follows the usual procedure of listing the values of $3\hbar^2/\mathcal{I}$, which is the excitation energy of the first rotational level (2+) in an even-even nucleus with a moment of inertia, $\mathcal{I}$. It has been found empirically[14,37] that odd-A nuclei have higher moments of inertia (i.e., lower values of $3\hbar^2/\mathcal{I}$) than do neighboring even-even nuclei. (Ta^{181} is slightly anomalous in this respect, having $3\hbar^2/\mathcal{I}=91$ kev while Hf^{180} and W^{182} have values 93 kev and 100 kev, respectively.) Very little is known about odd-odd nuclei, but they might be expected to have even larger moments of inertia than do odd-A nuclei.[38] In view of this, the moment of inertia implied by $I=3$ (in Table V) is surprisingly low. (The neighboring W^{183} has $3\hbar^2/\mathcal{I}=95$ kev after a correction is made for rotation-particle coupling[36]; without this correction $3\hbar^2/\mathcal{I}=78$ kev.) The moment of inertia given for $I=5$, $3\hbar^2/\mathcal{I}=74$ kev, would be reasonable for an odd-odd nucleus. Of course, if there is a deviation from a pure rotational spectrum, a correction may be needed in order to obtain the actual value of $\mathcal{I}$.

(3) *Magnetic g Factor.* The magnetic quantity $(g_\Omega-g_R)^2$ can be calculated[8,14,37] from the observed ratio of 172-kev photons to 319-kev photons if the intrinsic quadrupole moment, Q, is known. [The photon intensity ratio is proportional to $(g_\Omega-g_R)^2/Q_0^2$.] The well established systematics of nuclear quadrupole moments makes it clear that $Q_0=7\times10^{-24}$ cm^2 would be a good estimate for Ta^{182}, and this value was used to calculate the values of $\pm(g_\Omega-g_R)$ listed in Table V. If the reasonable estimate of $g_R=0.3$ is used, two alternative values of g_Ω can be listed corresponding to the two possible signs of $g_\Omega-g_R$. (Note that g_Ω is relatively insensitive to g_R except for high spin and negative values of $g_\Omega-g_R$).

(4) *Magnetic Moment.* The magnetic moment, μ, can be calculated from the formula $\mu=(\Omega g_\Omega+g_R)I/(I+1)$. For the ground-state rotational band, $\Omega=K=I$. The values of μ are listed in Table V. If $g_\Omega-g_R$ is positive, μ is quite large and relatively insensitive to I or to reasonable values of g_R. However if g_Ω is negative, μ does depend both on I and on g_R.

(5) *E_2 Admixtures in Predominantly M1 Transitions.* The predicted ratio for $M1$ to $E2$ photons depends on the same parameter which determines the competition between 319-kev and 172-kev photons (provided, of course, that the 147-kev and 319-kev levels are rotational). Table V lists these photon ratios for each of the different ground state spin possibilities. The E_2 mixing in the total transition probability would be somewhat smaller because the $M1$ conversion coefficients are larger; for the 147-kev transition, the factor by which the photon ratio would be multiplied is 1.36 while for the 172-kev transition it would be 1.32. Our measurements of conversion coefficients were not accurate enough to specify the exact E_2 mixing. (The theoretical 147-kev conversion coefficient varies only from 1.19 to 1.22 depending on the ground-state spin; the predicted 172-kev conversion coefficient varies only from 0.75 to 0.77.) However, it is conceivable that experiments more sensitive to the small $E2$ mixtures would help determine the ground state spin.

Comparison with the Nilsson-Mottelson Model

The parameters shown in Table V could be used to test some detailed model such as that given by Nilsson and Mottelson.[39,40] However, the model needs further development before it can be used unambiguously for odd-odd nuclei. Ambiguities exist even for a single odd particle; the 73rd proton might be in states $25(404\downarrow, 7/2+)$, $32(514\uparrow, 9/2-)$, or $31(402\uparrow, 5/2+)$, and the 109th neutron might be in $71(510\uparrow, 1/2-)$, $62(512\downarrow, 3/2-)$, or $48(503\uparrow, 7/2-)$. Furthermore, the interaction between the odd proton and the odd neutron might favor combinations of states which are higher in energy for an odd-A nucleus. Many combinations could then result. In attempting to find possible combinations which would give high-spin states for the isomer, we considered only the three proton states listed above but added three other neutron states: $45(615\uparrow, 11/2+)$, $40(505\downarrow, 9/2-)$ and $49(624\uparrow, 9/2+)$. An additional complication arises from possible mixtures of configurations for a state in an odd-odd nucleus.

The two possible couplings which exist for any particular combination of proton and neutron states

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Table VI. Combinations of single-particle states. (P refers to parallel intrinsic spins, A to antiparallel intrinsic spins.)

	Proton		Neutron						Combinations for isomer		
	State No.	Ω	State No.	Ω	Coupling	g_Ω[a]	μ[a]	Parity	P	N	Coupling
				Spin=3	($g_\Omega=1.8$ or -1.2; $\mu=3.8$ or -2.9)						
1	25	7/2	71	1/2	P	1	2.5	−	25	49	A
									32	48	P
2	31	5/2	71	1/2	P	1	2.4	−	31	45	P
3	32	9/2	62	3/2	P	1.6	3.8	+	25	40	P
4	31	5/2	45	11/2	A	−2.2	−4.8	+			
				Spin=4	($g_\Omega=1.3$ or -0.7; $\mu=4.4$ or -2.5)						
5	25	7/2	71	1/2	A	−0.2	−0.3	−	25	45	A
6	31	5/2	62	3/2	A	1.7	5.6	−	32	40	A
7	32	9/2	71	1/2	A	2.2	7.2	+	32	49	P
				Spin=5	($g_\Omega=1.0$ or -0.4; $\mu=4.4$ or -1.4)						
8	32	9/2	71	1/2	P	1.0	4.3	+	32	45	P
9	25	7/2	62	3/2	P	0.6	2.8	−		None	

[a] Asymptotic value; see reference 41.

introduce still another ambiguity. Some evidence has been presented[41] in favor of parallel coupling of intrinsic spin (Σ, shown by the arrows in the notation we use), as specified by the asymptotic quantum numbers (N, n_z, Λ, Σ).[39,40] On the other hand, there are some states for which neither Λ nor Σ are good quantum numbers and for which any coupling rule will depend on $\Omega=\Lambda+\Sigma$. (For example, at the distortions found near T^{182}, state 71 is characterized[40] by $\Lambda\Sigma \cong 90\%\ 0\uparrow+10\%\ 1\downarrow$.)

Despite these uncertainties (and partly to emphasize them), it is instructive to tabulate the combinations which produce spin values acceptable for Ta^{182}. We considered the three proton states and the six neutron states mentioned above. Of the 36 possible combinations, the nine listed in the rows of Table VI give spin values between 3 and 5.

The many possibilities listed in Table VI make it clear that the model, to be useful for odd-odd nuclei, must have more definite state and coupling predictions. If the positions of the single particle states individually dominated, combination 1 (with 25+49 for the isomer) would be most attractive. The asymptotic g_Ω and μ values would be more helpful if some systematics existed to indicate how close these asymptotic values should come to the experimental data.

There are clearly enough unknowns in odd-odd nuclei to make auxiliary experimental data very useful. A direct determination of the spin and magnetic moment of the Ta^{182} ground state would be particularly helpful.

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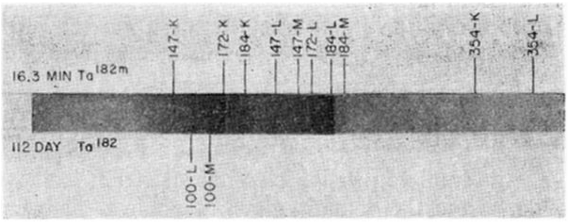

FIG. 1. Internal conversion electron spectrum of Ta^{182m}.