A small group in Ni^{58} was also seen at 5.1-Mev excitation. Its maximum cross section is less than 0.1 mb/sr. Another group was seen at 8.1-Mev excitation. Both of these groups are probably in phase with elastic scattering.

H. Groups in Ni^{60} at Higher Excitation than the 3^- Group

Angular distributions for the groups in Ni^{60} at 5.1, 5.6, 6.2, and 7.0 Mev are shown in Figs. 11 and 12. The angular distribution of the 5.1-Mev group is compared with the $L=4$ theoretical curve. The observed angular distribution is out of phase with elastic scattering. The data fit an $L=4$ curve better than an $L=2$ curve because the first maximum is at 19° c.m. rather than at 21° c.m. (where the $L=2$ curve has a maximum). The minima in the observed angular distribution are very shallow. This fact indicates that this group probably contains contributions from more than one level, and that some of these levels probably have angular distributions that are in phase with elastic scattering.

The group at 5.6 Mev is in phase with elastic scattering. The group at 6.2 Mev resembles the $L=3$ curve fairly closely. The 7.0-Mev group is in phase with elastic scattering. Moreover, the positions of the maxima in its angular distribution agree better with those of the 2.50-Mev group than with those of the $L=3$ curve. This group also resembles the 7.1-Mev group of Ni^{58}.

IV. ACKNOWLEDGMENTS

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Decay of 2.1-Hour Ta^{178}

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The allowed decay of 2.1-hr Ta^{178} has been reinvestigated, and the previously reported decay scheme has been almost completely confirmed. The multipolarity of the 331.7-kev transition between the 1480- and 1148-kev states has been reassigned as $M1$ on the basis of a measurement of its internal conversion coefficient. On the basis of the reassigned multipolarity, the beta-decay transition rates, and the recently measured spin 8 of the 1148-kev level, the 1148- and 1480-kev levels are interpreted, respectively, as two-proton and two-neutron states which are strongly admixed. The analysis in terms of two-particle states is based on ideas discussed in the following paper.

INTRODUCTION

In the experimental attempt to achieve a clearer understanding of the intrinsic states of deformed even-even nuclei, the allowed decays of both members of the Ta^{178} isomeric pair are excellent cases for study, as the allowed rate of the decays implies close similarity between the initial and final states. In an earlier paper the allowed decay of 9.3-min Ta^{178} was discussed.[1] The decay scheme of the 2.1-hr isomer has been studied in detail,[2–5] but, because of the importance of the Hf^{178} levels it populates to the general understanding of the problem of energy levels in even-even nuclei, we have thought it worthwhile to make some additional measurements. In the present paper we, therefore, review the previous experimental work on the 2.1-hr Ta^{178} decay, and report additional experimental data.

In the previous experiments the multipole assignments of the transitions were based largely on L-sub-

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[1] C. J. Gallagher, H. L. Nielsen, and O. B. Nielsen, Phys. Rev. **122**, 1590 (1961).

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shell conversion ratios because of the difficulty in obtaining accurate electron intensities from the spectrograms. While this is an extremely reliable method at low energies, it becomes much less reliable above about 250 kev. In the present experiment we have measured the electron intensities with a variable-field magnetic spectrometer to check the conversion coefficients of the higher energy transitions in the decay scheme, especially that of the 331.7-kev transition.

In a companion paper[6] the data on the decays of the two Ta^{178} isomers are summarized, and an attempt is made to show that the levels observed can be interpreted in a conceptually simple manner, if certain assumptions are made.

PREVIOUS EXPERIMENTAL RESULTS

The decay of 2.1-hr Ta^{178} was originally studied by Felber,[2] and Felber, Stephens, and Asaro,[3] (hereafter referred to as FSA) and by Carver and Turchinetz.[4] FSA produced their activity by a $Lu^{175}(\alpha,n)Ta^{178}$ reaction, and used high-resolution permanent-magnet spectrographs with photographic recording to measure the electron spectrum, and conventional gamma- amma coincidence spectroscopy to establish the cascade relationships. In addition they measured the 4.8-sec half-life of the 1148-kev isomeric level by chemical separation techniques.[7] The conclusions reached by Carver and Turchinetz, who used only gamma-ray spectroscopy, differ from those of FSA, but the conclusions based on the more detailed work of FSA seem clearly to be preferred. Recent measurements by Harmatz, Handley, and Mihelich, who also used high-resolution electron spectrographs but who had more intense sources than FSA, lend further support to FSA's conclusions, although these authors state that the 331.7-kev transition is $M1$ rather than $E2$ as reported by FSA.[5]

Deutsch and Bauer have recently measured angular correlations involving the 88.8-kev $E1$ transition, and have concluded that the spin of the 1148-kev level is 8.[8]

EXPERIMENTAL

Sources

The sources used in the present study were prepared by the $Lu^{175}(\alpha,n)Ta^{178}$ reaction in the Copenhagen cyclotron, using 18-Mev alpha particles. The chemical procedure used to separate the Ta^{178} (and a small amount of Ta^{177} and Ta^{179}) activity from the lutetium target was identical to that reported by Felber,[2] as was the ion exchange technique used to separate the 4.8-sec Hf^{178} isomer from its Ta parent. Beta spectrometer sources were prepared by evaporating a few drops of solution containing 100 μC of Ta^{178} activity on a 50-μg/cm^2 VYNS film.

Equipment

The gamma-ray measurements were made with conventional NaI(Tl) crystal detector, electronic circuits, and pulse-height analyzers, all of which have been described previously.[1] Internal conversion electron—gamma-ray coincidence measurements were made in the large Copenhagen six-gap orange spectrometer,[9] as were the internal-conversion electron intensity measurements.

Experimental Measurements and Results

(*a*). *Gamma rays.* Gamma-ray intensity measurements of the Ta^{178}-Hf^{178m} equilibrium mixture, and of Hf^{178m} alone were made. That of the latter was measured by extracting Hf^{178m} from Ta^{178} and counting for 20-sec intervals, then subtracting a 20-sec background from the spectrum. Sufficient statistics were obtained by summing a number of runs. The background subtraction and summing was done automatically. The spectrum of the isomer (minus one transition) has also been measured by electron—gamma-ray coincidences by gating with conversion electrons from one of the cascade transitions below the long-lived 1148-kev state.

(*b*). *Conversion electrons.* The electron spectrum was measured with the six-gap spectrometer, from 50 to 450 kev. Because of source thickness, no attempt was made to measure the intensity of the K line of the 88.8- and 93.1-kev transitions, whose K-conversion coefficients were measured absolutely by other methods (see below).

(*c*). *Conversion coefficients and multipolarity assignments.* The electron line intensities of the 213.6-, 325.7-, 331.7-, and 426.8-kev transitions, corrected for decay, and the gamma-ray intensities of these same transitions obtained as discussed above, have been normalized to Sliv and Band's theoretical K-conversion coefficients for a pure $E2$ transition of 213.6 kev.[10]

In Table II the theoretical K-conversion coefficients for $E1$, $E2$, $M1$, and $M2$ transitions for $Z=72$ and with energies equal to those observed in the present study are listed. A comparison of the experimental values of Table I with the theoretical values of Table II indicates that $\alpha_K(331.7)$ is consistent only with a pure $M1$ assignment for the 331.7-kev transition, or a predominantly magnetic dipole $M1+E2$ admixture, pure $E2$ being definitely excluded. $\alpha_K(93.1)$ has been measured[1] and is equal within experimental error to $\alpha_K(93.1)$ for a pure $E2$ transition.

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[7] FSA (reference 3) quote Cochran, Mize, and Bunker as having independently measured the 4.8-sec half-life of the isomer.
[8] M. Deutsch and R. W. Bauer, Nuclear Phys. **21**, 128 (1960).
[9] O. Kofoed-Hansen, J. Lindhard, and O. B. Nielsen, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd **25**, No. 16 (1950); O. B. Nielsen and O. Kofoed-Hansen, *ibid.* **29**, No. 6 (1955); K. M. Bisgaard, Internal report of the Physical Institute, Aarhus University, Aarhus, Denmark.
[10] L. A. Sliv and I. M. Band, Leningrad Physico-Technical Institute Reports (1956 and 1958); Reproduction: Reports ICC 57 K1 and ICC 58 L1, issued by the Physics Department, University of Illinois, Urbana, Illinois (unpublished).

TABLE I. Photon intensities, conversion coefficients, and multipolarity assignments for transitions in Hf^{178} following the decay of Hf^{178m} and the equilibrium mixture Ta^{178}-Hf^{178m}.

Energy of transition (kev)[a]	Hf^{178m} Photon intensity	Hf^{178m} K-conversion coefficient	Ta^{178}-Hf^{178m} Photon intensity	Ta^{178}-Hf^{178m} K-conversion coefficient	Multipolarity assignment
88.8		...[b]		...[b]	$E1$
	1.4		1.2		
93.1		...[b]		...[b]	$E2$
213.6	1.8	(0.135)[c]	1.7	(0.135)[c]	$E2$
325.7	2.0	0.043	2.3 {1.8	{0.0352 (0.043)[d]	$E2$
331.7			0.5	0.0267 0.13	$M1$
426.8	1.7	0.023	1.7	0.023	$E2$
K x-rays	1.3		3.0		

[a] Energies as reported by Felber, Stephens, and Asaro (reference 3).
[b] K electron lines badly absorbed in source. See Table II for the measured absolute conversion coefficients.
[c] Sliv and Band's theoretical K-conversion coefficient used for normalization.
[d] Value assumed to determine 331.7-kev photon contribution to composite gamma-ray peak.

$\alpha_K(88.8)$ was determined directly from a 100-channel analyzer spectrum of the photons coincident with the L line of the 93.1-kev transition. The ratio of the intensity of the K x-rays (corrected for K conversion of the higher energy transitions, except the 93.1, and the K-Auger effect) to the intensity of the 88.8-kev photon peak in the photon spectrum is the K-conversion coefficient of the 88.8-kev transition. The correction for K conversion of the higher energy transitions is 35% of the peak, where we have assumed that the other transitions are pure $E2$. $\alpha_K(88.8)$ thus determined is 0.69 ± 0.20, to be compared with the theoretical 0.40 for a pure $E1$ transition. The absolute value of the conversion coefficient is consistent only with a pure $E1$ assignment for the transition, plus a $\leq 0.7\%$ $M2$ admixture (see Table II). The high-resolution electron data appear to rule out any $M2$ admixture, however. The apparently large K-conversion coefficient may indicate anomalous behavior,[11] but it may also be due to the experimental uncertainty (which may be as great as 20%) in the relative gamma-ray peak-height efficiencies introduced by the large geometry and large probability for coincidence summing. The limit of error quoted applied only to the statistics of the measured intensities. Other experimental corrections, such as random coincidences and contributions to the K x-ray peak from coincidences with the underlying L 88.8-kev electrons and L 113-kev electrons from Ta^{177} are small.

TABLE II. Comparison of Sliv and Band's theoretical K-shell conversion coefficients for $E1$ (α_1), $E2$ (α_2), $M1$ (β_1), and $M2$ (β_2) transitions with the measured values for the transitions in Hf^{178} following 2.1-hr Ta^{178} decay. The assigned transition multipolarities are shown in column 7.

Energy of transition (kev)[a]	Theor. K-conversion coefficient α_1	α_2	β_1	β_2	Exp. K-conversion coefficient[b]	Assignment
88.8	0.40	1.15	5.0	40	0.69 ± 0.20[c]	$E1$
93.1	0.34	1.05	4.2	33	1.03 ± 0.15[d]	$E2$
213.6	0.042	0.135	0.39	1.9	(0.135)[e]	$E2$
325.7	0.014	0.044	0.13	0.46	0.043 ± 0.09	$E2$
331.7	0.013	0.042	0.12	0.43	0.13 ± 0.03	$M1$
426.8	0.0077	0.022	0.060	0.19	0.022 ± 0.004	$E2$

[a] Energies as reported by Felber, Stephens, and Asaro (reference 3).
[b] See text for a discussion of these values.
[c] Measured ratio of K-holes/88.8-kev photons coincident with L 93.1-kev internal conversion electrons. See text for corrections applied.
[d] Value reported in reference 1.
[e] $\alpha_K(E2)$ theor. of Sliv and Band used for normalization of the following three conversion coefficients. The $L_I/L_{II}/L_{III}$ ratios reported in references 3 and 5 are consistent with the assignment of pure $E2$ multipolarity to this transition.

d. Electron capture branching ratios. The electron capture branchings to the 1148- and 1480-kev levels are determined directly from the ratio $I_{326}/I_{332}=3.6\pm0.6$, where the transition intensities are the photon intensities corrected for internal conversion. Sliv and Band's K- and L-subshell conversion coefficients were used, and we assumed that the 331.7-kev transition is pure $M1$ and the 325.7-kev transition is pure $E2$. Theoretical α_L values were increased by 48% to account for M-, N-, and O-shell conversion. The total conversion coefficients thus obtained are 0.16 and 0.065 for the 331.7- and 325.7-kev transitions, respectively. From this we calculate relative branchings of $73\pm14\%$ and $27\pm6\%$ to the 1148- and 1480-kev levels, to be compared with the values $\approx60\%$ and $\approx40\%$ reported by FSA.

e. Comparative lifetimes. Log ft's to the two levels can be calculated if an electron-capture decay energy is estimated for the isomer. The decay energy of the 9.3-min isomer is 1912 kev. For reasons to be discussed we estimate a decay energy of 1912 ± 100 kev, from which we calculate (using Moszkowski's nomograph[12]) log ft's of 4.9 ± 0.2 and 4.9 ± 0.3 for the transitions to the 1148- and 1480-kev states.

DISCUSSION

In the following discussion we use the notation for single-particle states, the experimental data on single-particle states, and the coupling scheme for two-particle states in deformed nuclei discussed in the following paper.[6]

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[12] S. A. Moszkowski, Phys. Rev. **82**, 25 (1951).

The 2.1-Hour Ta^{178} State and the 1148-kev State in Hf^{178}

On the basis of the decay scheme, Ta^{178} has spin 7, 8, or 9, negative parity. An 8− configuration is not plausible because no reasonable combination of Nilsson states known in this region can combine so that $|\Omega_1 \pm \Omega_2| = 8-$. The choice is thus restricted to 7− or 9−.

We prefer the 7− assignment for several reasons. First, the measured ground-state spin of Ta^{181} is 7/2+, and the configuration [404↓] has been assigned to it, as well as to the Ta^{177} and Ta^{179} ground states. We therefore assume it is the lowest-lying proton state in Ta^{178}. The odd neutron is in the 105th neutron state, which has been measured as 7/2− in Hf^{177} and assigned the configuration [514↓], which has also been assigned as the ground state of the other 105-neutron nuclei Yb^{175} and W^{179}. The spin-coupling rules then predict that the ground state of Ta^{178} is the 7− configuration [404↓+514↓]. If the isomer has $K\pi = 7-$, then the 1+ isomer, whose configuration is unambiguous, is the first-excited state formed by promoting the 73rd proton from the 7/2+ state [404↓] to the 9/2− state [514↑]. The energy difference between these states in Ta^{181} is 6.3 kev and in Ta^{179} is 30 kev, making it seem quite probable that the state formed by promoting a proton has a lower energy than the other possible excitations. We expect, in fact, that the two levels are almost degenerate, and hence should be found as isomers. The 1912-kev decay energy used in calculating log *ft*'s above is assumed for this reason.

Second, the low log *ft* observed implies that the transition is the [514↑]⇄[514↓] transition, as this is the only single-particle transition with such a low log *ft* observed in adjacent odd-mass nuclei. Assuming the 7− configuration of Ta^{178}, this decay rate establishes the 1148-kev level as the 8− proton pair state [514↑+404↓].

A possible ambiguity exists, however, in the configuration assignments of the 2.1-hr Ta^{178} and 1148-kev levels. An alternative set of assignments which could also account for the fast transition rate in terms of the [514↑]⇄[514↓] transition is the assignment of Ta^{178} as the 9− configuration [514↑+624↑] and the 1148-kev level as the 8− two-neutron configuration [514↓+624↑]. We prefer the 7− assignment of Ta^{178} because it is in better agreement with the systematics of single-particle levels than the 9− assignment. The 8− assignment of the 1148-kev level as the two-proton state also seems preferable, because an 8− state is also observed in Hf^{180} at 1142 kev, and it is easier to understand the constant energy of the level in two isomers differing by two neutrons if the level is a two-proton level.

The 1480-kev Level

The 1480-kev state was previously assigned as a 9− rotational state based on the 1148-kev level.[3] However, if Ta^{178} has $K\pi = 7-$, the 9− rotational assignment is ruled out, and only 7− or 8− assignments are possible for the level.

Even if it is assumed that Ta^{178} has spin 9, the rotational assignment is still ruled out because the electron-capture branching to the 1148- and 1480-kev states is anomalous, and in such a way that it cannot be explained by perturbations introduced to date. That is, according to the strong coupling model, the branching ratio for beta branching to two states of the same rotational band should just be the ratio of the squares of two Clebsch-Gordan coefficients.[13] Experimentally these branching ratios generally differ somewhat from theory for transitions in which the matrix elements may not be the same for the transitions to both levels, but are much closer to the theoretical predictions when the matrix elements are the same.[14] The beta-decay matrix element assumed in the present case is the largest observed in this region, so that the mixing of any other intrinsic state in the rotational state will *decrease* the electron capture branching to it. The theoretical ratio is

$$\frac{ft(9-9 \to 8-8)}{ft(9-9 \to 9-8)} = 0.089,$$

whereas experimentally

$$\frac{ft(\text{EC of Ta}^{178}\text{ to 1148-kev level})}{ft(\text{EC of Ta}^{178}\text{ to 1480-kev level})} = 1.$$

The experimental ratio indicates a strongly *enhanced* transition to the supposed rotational state and hence the interpretation of the state as a rotational state is inconsistent with theory.

From the results of Sec. V of the following paper it is seen that low-lying 7− and 8− intrinsic states are predicted by the systematics. The 8− two-neutron state [624↑+514↓] is expected to be the lowest-lying two-neutron state. There should be two 7− states, a two-proton state [514↑+402↑] and a two-neutron state [624↑+512↑]; however, both 7− states are produced by exciting both particles and should have higher excitation energies than the 8− state, in which only one particle is excited. We believe the 8− assignment is preferable on the basis of the energies.

Rotational states based on both the 1148- and 1480-kev levels should be observed if the 8− interpretation of the 1148- and 1480-kev states is correct. The 9− state of each band should be populated with the theoretically expected branching ratio (see above) if Ta^{178} has spin 9, and will be populated only very weakly if the spin is 7. Hence, the apparent absence of transitions in the expected energy range (≈230 kev) and intensity deduced from the data reported by

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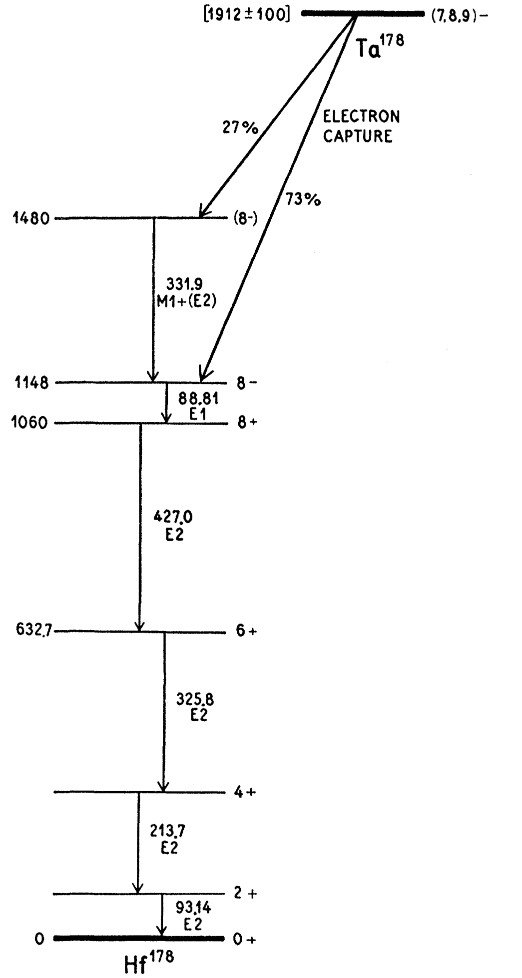

FIG. 1. Decay scheme of 2.1-hr Ta^{178} as reported by Felber, Stephens, and Asaro,[3] and as modified as a result of the measurements of Deutsch and Bauer,[7] Harmatz, Handley, and Mihelich,[5] and the present work.

Harmatz *et al.*[5] seems to support the 7− assignment of Ta^{178}. Gamma-ray branching from the 1480-kev level to the rotational state of the 1148-kev state band should be detectable, but on theoretical grounds should be reduced considerably relative to the 8− to 8− $M1$ transition by both the energy dependence and angular momentum recoupling factors.

While the points discussed above support the 8− assignment of the 1480-kev level, its assignment as the two-neutron state [624$\uparrow$+514$\downarrow$] does not explain why it is populated with such a large electron capture transition rate, nor why it decays by an $M1$ transition to the 1148-kev level, since both decay modes are strongly forbidden if the states are pure two-particle states. These transitions are also not explained if the state is assigned as either of the 7− states. An assumption which does explain the branching is that the 8− states are strongly admixed. The strength of the beta branching implies essentially complete admixture of the states. The $M1$ transition between the states supports the hypothesis of mixing. A measurement of the lifetime of the 1480-kev state would also test the strength of the mixing.

CONCLUSIONS

Our results support FSA's level scheme and multipolarity assignments for the 88.8-, 93.1-, 213.6-, 325.7-, and 426.8-kev transitions, but show that the multipolarity assignment of Harmatz *et al.* for the 331.7-kev transition is correct. We have checked the electron capture branching and improved slightly the accuracy of these measurements. The decay scheme as now known is shown in Fig. 1.

On the basis of our analysis of the level scheme, we conclude that the only interpretation leading to a consistent explanation of the 2.1-hr Ta^{178} decay scheme is to assign the Ta^{178} isomer as the $K\pi=7-$ configuration [404$\downarrow$+514$\downarrow$] and the 1148- and 1480-kev levels as the $K\pi=8-$ configurations [404$\downarrow$+514$\uparrow$] (two proton) and [514$\downarrow$+624$\uparrow$] (two neutron), and assume the configurations are completely mixed.

A number of measurements would help check our assumptions, but we believe the most important single measurement would be that of the spin of 2.1-hr Ta^{178}.

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