High-Resolution Study of (d,p) Reactions on Targets of W^{182}, W^{184}, and W^{186}†

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The $W^{182}(d,p)W^{183}$, $W^{184}(d,p)W^{185}$, and $W^{186}(d,p)W^{187}$ reactions have been studied with a magnetic spectrograph at a bombarding energy of 12 MeV and over a range of scattering angles. The ground-state Q values for the three reactions were found to be 3.967 ± 0.005, 3.524 ± 0.005, and 3.236 ± 0.005 MeV, respectively. The angular-distribution data distinguished between $l=1$ and $l=3$ transitions for most of the lower excited states. The theoretical differential cross sections and excitation energies were calculated with a computer code which uses the single-particle rotational model including band mixing. It was found with the aid of this code that all levels observed in W^{183}, W^{185}, and W^{187} up to an excitation energy of about 0.5 MeV could be consistently interpreted as arising from the $[510\frac{1}{2}^-]$, $[512\frac{3}{2}^-]$, and $[503\frac{7}{2}^-]$ intrinsic states. For W^{183}, good agreement is obtained between the observed differential cross sections and the cross sections calculated with the empirical parameters obtained by Kerman. Similar fits obtained for W^{185} and W^{187} lead to probable determinations of the J and K quantum numbers of the low-lying levels. The highly excited states in W^{183}, W^{185}, and W^{187} do not appear to be easily interpreted with the same rotational model. Theoretical (d,p) spectra in which only intrinsic and rotational states of the Nilsson model are considered bear little resemblance to the observed spectra at high excitation energy.

INTRODUCTION

HIGH-RESOLUTION studies[1–4] of deformed heavy nuclei with magnetic spectrographs and Van de Graaff accelerators are a relatively recent development. This new method of investigation can aid in the study of these deformed nuclei in a number of unique ways. Besides simply locating energy levels for cataloging purposes, the method in many situations can identify the spins and Nilsson states[5] of the levels. Some information about the validity of various nuclear models can also be gained. In particular, the predictions of the RPC model[6] (rotation and particle motion with Coriolis band mixing) can be tested. The present paper applies these objectives to the study of the well-known nucleus W^{183} and its neighboring odd-A nuclei W^{185} and W^{187} by means of the (d,p) reaction.

The isotope W^{183} has been the subject of extensive experimental measurements[7] and theoretical calculations.[8,9] In particular, the excitation energies and the gamma-ray transitions of low-lying states have been precisely measured with a bent-crystal spectrometer. These excitation energies and gamma-ray intensities were analyzed by Kerman[8] and recently by Brockmeier *et al.*[9] with the RPC model. The excellent agreement which is achieved between theory and experiment probably makes W^{183} the best known of all odd-A deformed nuclei. Consequently, this nucleus provides a good check on the method of studying deformed nuclei by means of high-resolution charged-particle reactions. The $W^{182}(d,p)W^{183}$ reaction has previously been investigated by Isoya.[10] However, his over-all resolution of about 100 keV was inadequate to resolve any of the individual final states. Neither the $W^{184}(d,p)W^{185}$ reaction nor the $W^{186}(d,p)W^{187}$ reaction has been studied previously.

In the calculation of spectra from (d,p) reactions on deformed nuclei, one can expand the wave function of a Nilsson state into a particular set of amplitudes c_{jl} of spherical-well eigenfunctions, where j and l are the total and orbital angular momenta, respectively.[11] In a particular nuclear reaction, these c_{jl} determine the observed differential cross sections of the various members of the rotational band built upon the Nilsson state. For a (d,p) reaction on an even-even nucleus, the relation for the differential cross section is especially simple, namely $d\sigma=2c_{jl}^2\phi_l$, where ϕ_l is the intrinsic single-particle cross section.[11] Consequently, the complete spectra of an isolated Nilsson state will appear as a series of groups separated in energy according to the well known formula $E=AJ(J+1)$, where $A=\hbar^2/2\mathcal{I}$ is the unit of rotational energy ($\mathcal{I}$ being the moment of inertia) and J is the total angular momentum of the state. The relative intensities of these groups depend on the particular set of c_{jl} which make up the Nilsson state.

In the present reactions on tungsten, the Nilsson states are not well separated and, in addition, there is some band mixing between the various Nilsson states. As a result, the simple ideal spectra from the various Nilsson states are not easily recognized in the present data. One has no choice but to do a calculation in which

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cross sections of the various states are calculated exactly and the complications introduced by the RPC model are adequately treated.

Theoretical predictions of the differential cross sections and excitation energies for the model of a rotator plus an odd nucleon were carried out with a computer code which has been previously described[1] in part. In dealing with W^{183}, W^{185}, and W^{187}, it is necessary to use a code that has provisions for band mixing since a considerable amount of band mixing is present between the $K=\frac{1}{2}$ and $K=\frac{3}{2}$ rotational bands. The code described in Ref. 1 was modified to handle odd-A final states by including a term to handle decoupling effects for $K=\frac{1}{2}$ bands. Input parameters are the moments of inertia, quantum numbers, and Nilsson wave functions of the various intrinsic states one wishes to consider, as well as the relative positions of the intrinsic states. The mixing coefficients $\langle J_- \rangle$ and decoupling parameter a can be either calculated directly from the Nilsson wave functions or read in separately as empirical parameters. The differential cross section is obtained from the expression

$$d\sigma/d\Omega = [(2I_2+1)/(2I_1+1)]\mathcal{S}\phi_l,$$

where I_1 and I_2 are the spins of the target and residual nucleus, respectively, and $\mathcal{S}$ is the spectroscopic factor. The latter is based on Satchler's expression[11] for reduced widths amplitudes for stripping on deformed nuclei. Band-mixing effects in the calculation of $\mathcal{S}$ as well as the excitation energies were obtained by diagonalizing the Hamiltonian matrix in which

$$H_{ii} = A_i[J(J+1) - K_i(K_i+1) + \delta_{K_i 1/2} a_i (J+\tfrac{1}{2})(-1)^{J+1/2}] + E_i^0 \quad \text{for} \quad J \geqslant K_i,$$
$$= 0 \quad \text{for} \quad J < K_i,$$
$$H_{ij} = H_{ji} = -\tfrac{1}{2}(A_i + A_j)[(J+K_i)(J-K_i+1)]^{1/2}\langle J_- \rangle_{ij} \quad \text{for} \quad J \geqslant K_i \quad \text{and} \quad K_i = K_j + 1,$$
$$= 0 \quad \text{for} \quad J < K_i, \quad J < K_j, \quad \text{or} \quad |K_i - K_j| \neq 1,$$

where K_i is the projection of the total angular momentum J on the symmetry axis, a_i is the decoupling coefficient, E_i^0 is the position of the intrinsic state, and $\langle J_- \rangle_{ij}$ is an adjustable parameter which determines the strength of the mixing. No coupled-channel effects[12] nor pairing-correlation effects[13] were included explicitly in this calculation performed by the computer code.

A rough calculation of the differential cross sections expected when the effects of pairing correlations are included was made by reducing the amplitude of the Nilsson wave functions by the factor U^2, the probability that a particular Nilsson state is unoccupied by a pair of neutrons. That is, the differential cross sections were calculated with $U_j \theta_i{}^j$ substituted for $\theta_i{}^j$ in Eq. (10) of Ref. 1. A more rigorous calculation was not attempted.

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EXPERIMENTAL PROCEDURE

The data were taken with the Argonne broad-range magnetic spectrograph and a 12-MeV deuteron beam from the Argonne tandem Van de Graaff. This system has been described in an earlier paper.[14] The targets were made from separated isotopes of tungsten (obtained from Oak Ridge National Laboratory) which were evaporated in the form of tungsten trioxide onto a thin self-supporting backing of carbon with a Formvar substrate. The durability of the target was found to be considerably improved by adding a Formvar film. Target thicknesses ranged from 50 to 100 $\mu g/cm^2$. A hollow tubular boat heated by electrical conduction was used. With this boat, only about 5 mg of separated isotope were required for each target. The boat was made by squeezing together both ends of a tantalum tube with $\frac{1}{4}$-in. o.d. and 0.010-in. wall thickness and drilling a 1-mm hole through the wall.

A contaminant of Na^{23} was present on some of the targets. However, the proton groups from this contaminant were easily identified by means of their rapid change in energy as a function of scattering angle.

Angular-distribution data on the $W^{184}(d,p)W^{185}$ and $W^{186}(d,p)W^{187}$ reactions were taken at scattering angles between 20° and 90°. Data on the $W^{182}(d,p)W^{183}$ reaction between scattering angles of 5° and 140° have also been obtained and are being reported separately[15] in a study on the reaction mechanism for the $W^{182}(d,p)W^{183}$ reaction at 12-MeV bombarding energy. The angular-distribution data were taken with the help of a target monitor system which used a solid-state detector. A single-channel analyzer was set on the group of deuterons which were elastically scattered from the tungsten in the target. This procedure compensated for changes in target thickness and the efficiency of beam-current integration.

Absolute differential cross sections were measured by comparing the yield of the various levels in the (d,p) reaction with the yield of deuterons elastically scattered off tungsten nuclei. The elastic-scattering cross sections were taken from Ref. 15.

Two doublets (groups Nos. 4, 5 and 7, 8) in the $W^{182}(d,p)W^{183}$ reaction data were unfolded with the aid of a computer program. The computer was given a nearby singlet group as a standard peak and asked to find the best fit to the data by adjusting the doublet spacing and relative amplitudes. The excitation energies of the 309- and 484-keV levels in W^{183} were found in this way.

EXPERIMENTAL RESULTS

Proton spectra recorded at 60° scattering angle with targets of W^{182}, W^{184}, and W^{186} and with a bombarding energy of 12 MeV are shown in Figs. 1–3. Figure 4 shows a portion of the proton spectrum from the

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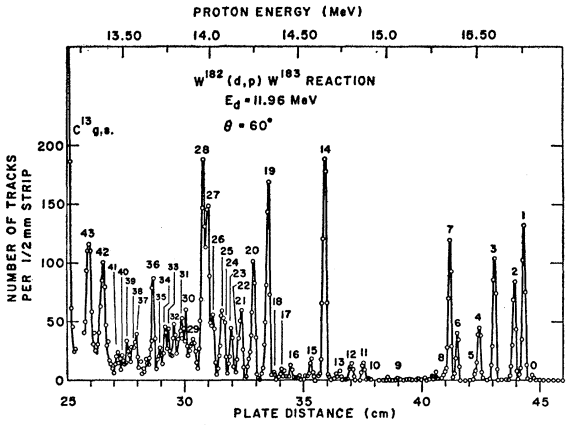

FIG. 1. Spectrum of protons observed at 60° from a W^{182} target bombarded with 11.96-MeV deuterons.

$W^{182}(d,p)W^{183}$ reaction where the signal-to-noise ratio has been enhanced by superimposing data taken at 80°, 90°, 100°, 130°, and 145°. Proton groups corresponding to levels No. 8, 9, and 10 in W^{183} show up more clearly in this figure. A weak proton group from a level at 554.326 keV reported for W^{183} by Edwards *et al.*[7] would probably be obscured by groups from the contaminant reaction $W^{184}(d,p)W^{185}$. The W^{182} target contained a 2.5% impurity of W^{184} as well as a 2.5% impurity of W^{183}. The $W^{183}(d,p)W^{184}$ reaction was run separately with an enriched target. No groups in Fig. 4 could be attributed to the latter reaction. The few other very weak groups in Fig. 4 could not be definitely identified.

Excitation energies and Q values observed for the states of W^{183}, W^{185}, and W^{187} are listed in Tables I–III. Energy level diagrams for each of these nuclei are presented in Figs. 5–7. The standard error for each of the ground-state Q values is estimated to be 5 keV. For W^{183}, the accuracy of the excitation energies for groups No. 1, 2, 3, 4, 6, and 7 is estimated at 2 keV. For groups No. 5 and 8, which are members of close doublets and were unfolded by a computer fitting program, the estimated error is 3 keV. For all other levels, the estimated uncertainty is 5 keV.

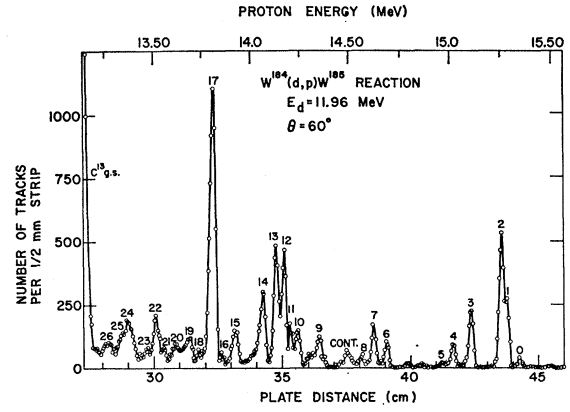

FIG. 2. Spectrum of protons observed at 60° from a W^{184} target bombarded with 11.96-MeV deuterons.

TABLE I. Excitation energies, Q values, differential cross sections, and quantum numbers l, J, and K for the levels in W^{183} formed through the $W^{182}(d,p)W^{183}$ reaction.

Level	E_x[a] (MeV)	Q[b] (MeV)	$\frac{d\sigma}{d\Omega}(60°)$[c] (mb/sr)	l[d]	J[e]	K[e]
0	0.0	3.967	0.015	1	$\frac{1}{2}$	$\frac{1}{2}$
1	0.046	3.921	0.34	1	$\frac{3}{2}$	$\frac{1}{2}$
2	0.099	3.868	0.22	3	$\frac{5}{2}$	$\frac{1}{2}$
3	0.209	3.758	0.28	1	$\frac{3}{2}$	$\frac{3}{2}$
4	0.292	3.675	0.11	3	$\frac{5}{2}$	$\frac{3}{2}$
5	0.309	3.658	0.02	5	$\frac{9}{2}$	$\frac{1}{2}$
6	0.412	3.555	0.10	3	$\frac{7}{2}$	$\frac{3}{2}$
7	0.453	3.514	0.31	3	$\frac{7}{2}$	$\frac{7}{2}$
8	0.484	3.483	0.01			
9	0.741	3.226	0.005			
10	0.913	3.054	0.005			
11	0.939	3.028	0.039			
12	1.005	2.962	0.043			
13	1.072	2.895	0.024			
14	1.156	2.811	0.56			
15	1.229	2.738	0.052			
16	1.338	2.629	0.02			
17	1.382	2.585	0.023			
18	1.437	2.530	0.009			
19	1.474	2.493	0.48			
20	1.558	2.409	0.32			
21	1.636	2.331	0.13			
22	1.663	2.304	0.08			
23	1.689	2.278	0.12			
24	1.731	2.236	0.11			
25	1.743	2.224	0.14			
26	1.789	2.178	0.14			
27	1.820	2.147	0.46			
28	1.847	2.120	0.52			
29	1.893	2.074	0.11			
30	1.942	2.025	0.052			
31	1.960	2.007	0.11			
32	2.007	1.960	0.070			
33	2.044	1.923	0.048			
34	2.061	1.906	0.063			
35	2.092	1.875	0.049			
36	2.130	1.837	0.22			
37	2.226	1.741	0.084			
38	2.256	1.711	0.047			
39	2.279	1.688	0.058			
40	2.308	1.659	0.027			
41	2.330	1.637	0.057			
42	2.412	1.555	0.47			
43	2.500	1.467	0.59			

[a] The estimated uncertainty is 2 keV for levels Nos. 1, 2, 3, 4, 6, and 7; 3 keV for levels Nos. 5 and 8; and 5 keV for the other levels.
[b] The estimated uncertainty in the ground-state Q value is 5 keV.
[c] The estimated uncertainty in the absolute cross sections is about 15%. The uncertainty in cross section of one level relative to another is about 10% for the strong groups.
[d] The l values are obtained from the known initial- and final-state spins.
[e] These values of J and K were determined by the decay studies (Ref. 7).

The absolute differential cross section measured for each of the levels at 60° scattering angle is also given in

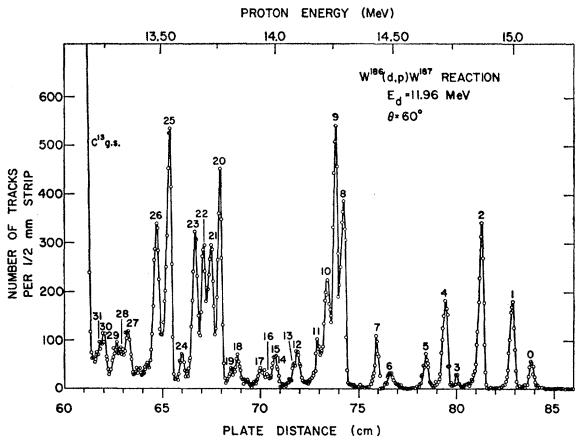

FIG. 3. Spectrum of protons observed at 60° from a W^{186} target bombarded with 11.96-MeV deuterons.

Tables I–III. The estimated accuracy of the cross sections relative to each other is about 5% for the strong groups. As absolute measurements, these cross sections have an estimated accuracy of about 15%. The values of the orbital angular momentum l for the captured neutron in transitions to a particular level are also given in Tables I–III. For completeness, these tables also include values of J and K assigned in accordance with the rotational-model calculation described below.

TABLE II. Excitation energies, Q values, differential cross sections, and suggested quantum numbers for the levels in W^{185} formed through the $W^{184}(d,p)W^{185}$ reaction.

Level	E_x[a] (MeV)	Q[b] (MeV)	$\frac{d\sigma}{d\Omega}(60°)$[c] (mb/sr)	l[d]	J[e]	K[e]
0	0.0	3.524	0.038	(1)	$\frac{3}{2}$	$\frac{3}{2}$
1	0.060	3.464	0.30	3	$\frac{5}{2}$	$\frac{3}{2}$
2	0.085	3.439	0.65	1	$\frac{3}{2}$	$\frac{1}{2}$
3	0.237	3.287	0.29	3	$\frac{7}{2}$	$\frac{7}{2}$
4	0.327	3.197	0.091	3	$\frac{7}{2}$	$\frac{1}{2}$
5	0.373	3.151	0.015	(3)		
6	0.660	2.864	0.12	(1)		
7	0.723	2.801	0.19	(3)		
8	0.784	2.740	0.045	(1)		
9	0.996	2.528	0.13			
10	1.102	2.422	0.17			
11	1.136	2.388	0.13			
12	1.174	2.350	0.48			
13	1.210	2.314	0.54			
14	1.279	2.245	0.44			
15	1.418	2.106	0.23			
16	1.489	2.035	0.040			
17	1.533	1.991	0.016			
18	1.612	1.912	0.027			
19	1.649	1.875	0.19			
20	1.717	1.807	0.08			
21	1.785	1.739	0.075			
22	1.821	1.703	0.24			
23	1.877	1.647	0.042			
24	1.949	1.575	0.32			
25	2.000	1.524	0.067			
26	2.067	1.457	0.096			

[a] The estimated uncertainty in the excitation energies is 5 keV.
[b] The estimated uncertainty in the ground-state Q value is 5 keV.
[c] The estimated uncertainty in the absolute cross sections is about 15%. The uncertainty in cross section of one level relative to another is about 10% for the strong groups.
[d] These l values were obtained from angular-distribution measurements. The parentheses indicate less certain assignments.
[e] These spins are suggested by an analysis of the data by use of the rotational model with band mixing.

TABLE III. Excitation energies, Q values, differential cross sections, and suggested quantum numbers for the levels in W^{187} formed through the $W^{186}(d,p)W^{187}$ reaction.

Level	E_x[a] (MeV)	Q[b] (MeV)	$\frac{d\sigma}{d\Omega}(60°)$[c] (mb/sr)	l[d]	J[e]	K[e]
0	0.0	3.236	0.078	1	$\frac{3}{2}$	$\frac{3}{2}$
1	0.079	3.157	0.25	3	$\frac{5}{2}$	$\frac{3}{2}$
2	0.205	3.031	0.47	1	$\frac{3}{2}$	$\frac{1}{2}$
3	0.304	2.932	0.021	3	$\frac{5}{2}$	$\frac{1}{2}$
4	0.351	2.885	0.25	3	$\frac{7}{2}$	$\frac{7}{2}$
5	0.434	2.802	0.092	3	$\frac{7}{2}$	$\frac{1}{2}$
6	0.592	2.644	0.049	(1)		
7	0.642	2.594	0.12	(1)		
8	0.782	2.454	0.58	(1)		
9	0.813	2.423	0.60	(1)		
10	0.844	2.392	0.21			
11	0.889	2.347	0.045			
12	0.974	2.262	0.077			
13	0.992	2.244	0.048			
14	1.070	2.166	0.025			
15	1.087	2.149	0.065			
16	1.107	2.129	0.019			
17	1.145	2.091	0.049			
18	1.234	2.002	0.074			
19	1.266	1.970	0.033			
20	1.316	1.920	0.48			
21	1.349	1.887	0.39			
22	1.379	1.857	0.30			
23	1.416	1.820	0.40			
24	1.476	1.760	0.051			
25	1.536	1.700	0.72			
26	1.591	1.645	0.44			
27	1.711	1.525	0.12			
28	1.755	1.481	0.054			
29	1.774	1.462	0.082			
30	1.819	1.417	0.080			
31	1.843	1.393	0.070			

[a] The estimated uncertainty in the excitation energies is 5 keV.
[b] The estimated uncertainty in the ground-state Q value is 5 keV.
[c] The estimated uncertainty in the absolute cross sections is about 15%. The uncertainty in cross section of one level relative to another is about 10% for the strong groups.
[d] The l values were obtained from angular-distribution measurements. The parentheses indicate less certain assignments.
[e] These spins are suggested by an analysis of the data by use of the rotational model with band mixing.

For W^{183}, l values of the transitions are inferred from the known spins and parities of these levels. The l values assigned to the transitions which lead to levels in W^{185} and W^{187} were obtained from the angular-distribution data in the following way. Only $l=1$, 3, and 5 transitions are expected near the ground state since in this region all Nilsson levels with large stripping cross sections have odd parity. This simplifies the problem of assigning l

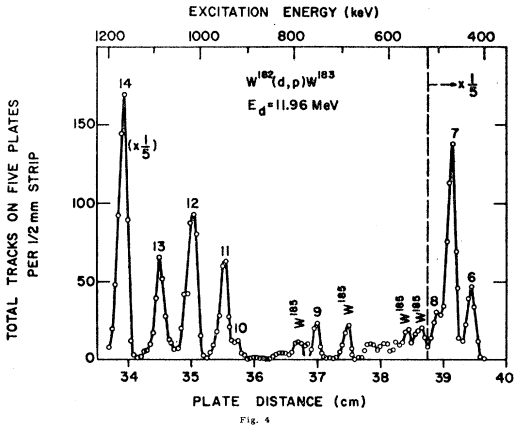

FIG. 4. Detail of proton spectrum from the $W^{182}(d,p)W^{183}$ reaction at 60°. The region from 400 to 1200 keV excitation in W^{183} is shown.

values; one then needs only to distinguish between $l=1$ and $l=3$ transitions since $l=5$ transitions will be very weak. The study of the $W^{182}(d,p)W^{183}$ reaction[15] showed that $l=1$ and $l=3$ transitions have angular distributions which differ considerably at the far forward angles. This behavior can be seen in Fig. 8, which shows angular-distribution data taken from Ref. 15 for $l=1$ and $l=3$ transitions in the $W^{182}(d,p)W^{183}$ reaction. The solid curves are angular distributions calculated by the

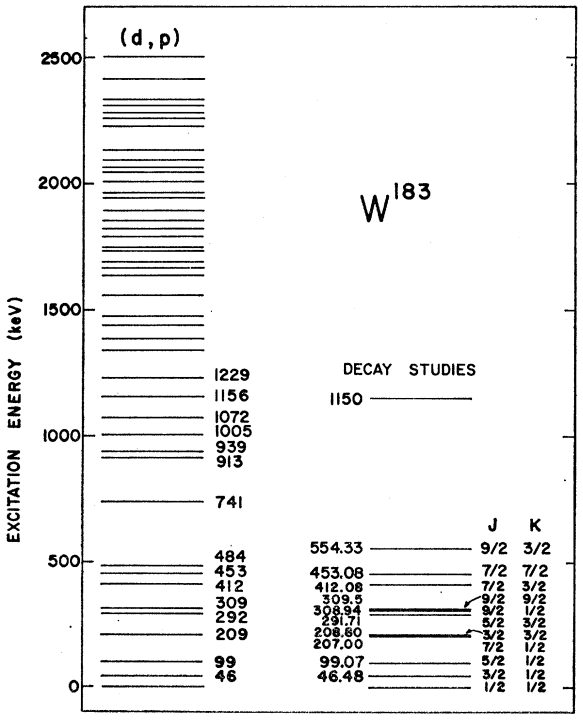

FIG. 5. Energy-level diagram of W^{183}. Levels observed in the present (d,p) study and previous decay studies are shown. Some of the levels are labeled with the values of J (total angular momentum) and K (projection of J on the nuclear symmetry axis) from the decay studies.

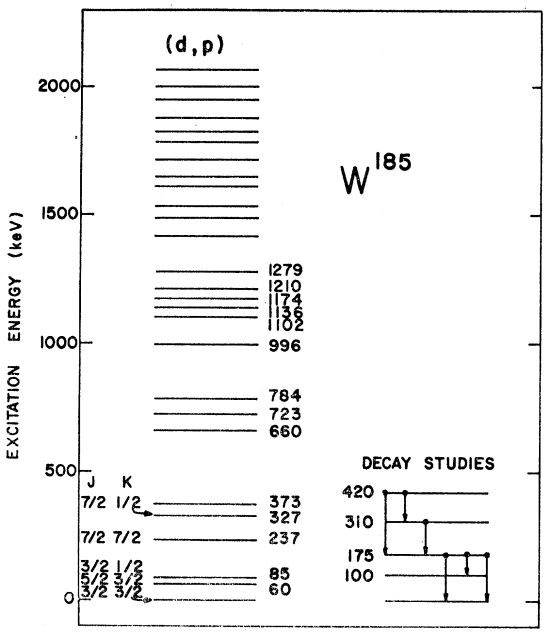

FIG. 6. Energy-level diagram of W^{185}. Levels observed in the present (d,p) study, and a decay scheme based on observed gamma rays are shown. The values of J and K obtained from the analysis of the present (d,p) data are shown.

distorted-wave Born approximation (DWBA) stripping theory which will be discussed below. For the $l=1$ transition, the data show that the cross section falls by a factor of about 1.15 from 80° to 30° scattering angle. However, for $l=3$ transitions the cross section decreases by a factor of about 1.90 over the same angular range. The changes in cross section from 80° to 30° scattering angle for the various low-lying levels observed in the present study are given as ratios in Table IV. These data show that groups Nos. 0 and 2 in both W^{185} and in W^{187} have significantly smaller ratios than the other levels and, hence, are assigned $l=1$. The other groups

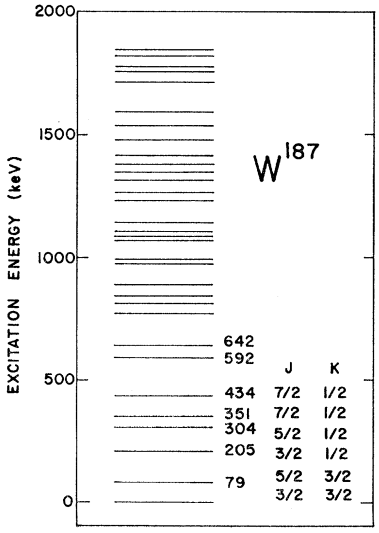

FIG. 7. Energy-level diagram of W^{187}, showing levels observed in the present (d,p) study. The values of J and K obtained from the analysis of the present data are shown.

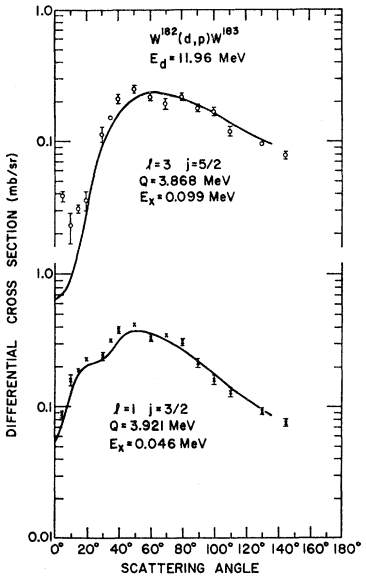

FIG. 8. Angular distributions of $l=1$ and $l=3$ levels observed in the $W^{182}(d,p)W^{183}$ reaction. The solid curves are theoretical angular distributions calculated with DWBA direct-reaction theory.

are assigned $l=3$ since this is the only other l value expected with a large cross section. Tentative l values are given to a few of the higher excited states in W^{185} and W^{187} on the basis of the 80°-to-30° cross-section ratios.

TABLE IV. Ratios of differential cross sections at 80° to those at 30° for levels observed with the $W^{182}(d,p)W^{183}$, $W^{184}(d,p)W^{185}$, and $W^{186}(d,p)W^{187}$ reactions.

Nucleus	Level	Cross-section ratio $d\sigma(80°)/d\sigma(30°)$	l
W^{183}	1	1.25±0.1	1
	2	1.80±0.2	3
	3	1.10±0.1	1
	7	2.0 ±0.15	3
W^{185}	0	0.9 ±0.3	1
	1	2.1 ±0.2	3
	2	1.40±0.1	1
	3	2.36±0.2	3
	4	3.1 ±0.6	3
	5	2.5 ±1.0	(3)
	6	1.41±0.3	(1)
	7	2.14±0.3	(3)
	9	1.45±0.3	(1)
W^{187}	0	1.05±0.2	1
	1	2.83±0.2	3
	2	1.24±0.1	1
	3	2.1 ±0.6	3
	4	2.64±0.2	3
	5	2.9 ±0.4	3
	6	1.0 ±0.3	(1)
	7	0.85±0.2	(1)
	8	1.45±0.2	(1)
	9	1.25±0.2	(1)

DISCUSSION

Ground-State Q Values

The neutron separation energies S_n calculated for W^{183}, W^{185}, and W^{187} from the ground-state Q values reported in the present study are given in Table V. (A deuteron binding energy of 2.225 MeV has been used.) The table also lists the values for these separation energies reported in the literature.[16–20] For W^{183}, the separation energy obtained by Bartholomew *et al.*[19] using the $W^{182}(n,\gamma)W^{183}$ reaction is in excellent agreement with the number derived from the present work. In addition, within the stated uncertainties, the most recent mass-spectrograph measurement of Bhanot *et al.*[16] agrees with the separation energy from the present work. For W^{185}, the separation energy reported by Kinsey and Bartholomew is in agreement with the present work. The only previous measurement on W^{187} is that of Treado and Chagnon[18] who give no uncertainties with their measurements.

TABLE V. A comparison of neutron separation energies S_n for W^{183}, W^{185}, and W^{187}.

Nucleus	S_n	Author
W^{183}	6.192±0.010 MeV	Present work
	6.233±0.037	Bhanot *et al.*[a]
	6.29 ±0.05	Geller *et al.*[b]
	6.10	Treado and Chagnon[c]
	6.192±0.008	Bartholomew *et al.*[d]
W^{185}	5.749±0.010 MeV	Present work
	5.77 ±0.02	Kinsey and Bartholomew[e]
	5.86	Treado and Chagnon[c]
W^{187}	5.461±0.010	Present work
	5.34	Treado and Chagnon[c]

[a] Reference 16. [b] Reference 17. [c] Reference 18. [d] Reference 19. [e] Reference 20.

Comparison of the Observed Energy Levels with Previous Studies

The W^{183} energy levels found in the present (d,p) study are shown in Fig. 5 together with levels observed in earlier gamma-ray studies.[7] The energy levels observed at low excitation with the (d,p) reaction are quite consistent with the levels observed in the decay studies. Levels at 207.0 and 309.5 keV were not observed in the (d,p) study, presumably because of their closeness to other levels with larger cross sections. No definite evidence was obtained for a level at 554.326 keV, but a proton group corresponding to such a level may have been obscured by contaminant groups. It is surprising that the level seen at 484 keV in the (d,p) studies was not observed in the decay studies.

The energy levels of W^{185}, both those observed in the present (d,p) work and those reported by Morinaga and

[16] V. B. Bhanot, W. H. Johnson, Jr., and A. O. Nier, Phys. Rev. **120**, 235 (1960).
[17] K. N. Geller, J. Halpern, and E. G. Muirhead, Phys. Rev. **118**, 1302 (1960).
[18] P. A. Treado and P. R. Chagnon, Nucl. Phys. **34**, 623 (1962).
[19] G. A. Bartholomew, J. K. Knowles, P. J. Campion, Chalk River Laboratory Report AECL 954 43, 1960 (unpublished).
[20] B. B. Kinsey and G. A. Bartholomew, Can. J. Phys. **31**, 1051 (1953).

Nagatani,[21] are displayed together in Fig. 6. On the basis of the γ rays observed in their study of the decay of Ta^{85}, the latter proposed an energy level diagram of W^{185}. The level schemes do not agree at all. However, it may be possible to fit the γ-ray transitions of Morinaga and Nagatani into the (d,p) level scheme. For example, their 245-keV gamma ray may correspond to a transition from the 235-keV level to the ground state, as seen in the (d,p) work. The decay of metastable W^{185} has been studied by Kramer and Wohl[22] who report three gamma-ray transitions with energies of 60 ± 2, 131 ± 2, and 175 ± 2 keV. These energies are consistent with the energies expected for gamma-ray transitions which involve the 373-, 237-, and 60-keV levels observed in the present (d,p) study of W^{185}. This agreement may, however, be purely accidental.

Rotational-Model Calculations

Theoretical proton spectra for (d,p) reactions on W^{182}, W^{184}, and W^{186} were calculated by a computer code (described above) which used the model of a symmetric rotator plus an odd nucleon. The objective of these calculations was to see how well the differential cross sections predicted by the model agreed with the experimental data on W^{183} and then to try to use the theoretical calculations to identify the character of the various new states observed in W^{185} and W^{187}.

At first, attempts were made to fit the observed $W^{182}(d,p)W^{183}$ spectra by a consistent use of the rotational model. That is, the energies of the intrinsic states, the mixing coefficient $\langle J_- \rangle$, and the decoupling parameter a were obtained directly from the Nilsson eigenvalues and Nilsson wave functions. No set of the Nilsson parameters (η, μ, and κ) could be found that gave a reasonable fit to the observed spectra. Some improvement was obtained by adjusting the energies of the intrinsic states empirically. However, the best agreement is obtained if a, $\langle J_- \rangle$, and the intrinsic energies E_i^0 are set equal to the empirical values found by Kerman.[8] An indication of the failure to fit the observed spectra of W^{183} when calculated values of a and $\langle J_- \rangle$ are used is found in Table VI, where Kerman's empirical values for a and $\langle J_- \rangle$ are given, together with values calculated from two different sets of Nilsson wave functions. Nilsson's choice of the parameters μ and κ and a deformation $\eta=4$ result in a value of a which has the correct magnitude but opposite sign from the empirically required a. Furthermore, the calculated value of $\langle J_- \rangle$ is much too small. Brockmeier *et al.*[9] give a set of values of η, μ, and κ that leads to the correct sign for a. However, this set also leads to a value of $\langle J_- \rangle$ that is still much smaller than the $\langle J_- \rangle$ required by the experimental data.

TABLE VI. Values of the decoupling parameter a for the $[510\frac{1}{2}^-]$ state and mixing coefficient $\langle J_- \rangle$ between the $[510\frac{1}{2}^-]$ and $[512\frac{3}{2}^-]$ states for W^{183}.

Author	a	$\langle J_- \rangle$
Kerman[a]	0.1684	1.4537
Nilsson[b]	−0.1692	0.913
Brockmeier *et al.*[c]	0.1948	0.929

[a] Reference 7.
[b] Reference 5 ($\eta=4.04$, $\mu=0.45$, and $\kappa=0.05$).
[c] Reference 8 ($\eta=4.04$, $\mu=0.34$, and $\kappa=0.05$).

[21] H. Morinaga and K. Nagatani, Nucl. Phys. **19**, 327 (1960).
[22] H. J. Kramer and W. H. Wahl, Bull. Am. Phys. Soc. **8**, 71 (1963).

The spectrum for the $W^{182}(d,p)W^{183}$ reaction was calculated with parameters which were chosen in the following way. The rotational-model parameters used are those found empirically by Kerman.[8] He was able to fit the highly accurate excitation energies measured by Murray *et al.*[7] to within 0.2 keV. Recently, Brockmeier *et al.*[9] were able to improve the fit to the measured energies by an order of magnitude in χ^2, by including seven more intrinsic states in the calculation. The new rotational-model parameters which they find produce only a slight change in the stripping cross section. Consequently, Kerman's parameters are adequate for the purposes of the present calculation. For W^{183} as well as for W^{185} and W^{187}, the Nilsson wave functions for a deformation $\eta=4$ were adopted since the calculated differential cross sections are not very sensitive to the deformation. Only the $[510\frac{1}{2}^-]$, $[512\frac{3}{2}^-]$, and $[503\frac{7}{2}^-]$ intrinsic states[23] have been used in the calculation. The intrinsic single-particle cross sections were calculated by the DWBA direct-interaction code TSALLY.[24] The optical parameters chosen were suggested by the work of Perey and Perey.[25] The particular set used is listed in Table VII. The calculated angular distributions for $l=1$ and $l=3$ neutron capture are shown in Fig. 8 as the curves through the data points. In plotting these curves the intrinsic single-particle cross sections have been multiplied by the factors 0.78 and 0.62 to fit the $l=1$ and $l=3$ experimental data, respectively. There is fairly good agreement between the shapes of the experimental and theoretical curves. This suggests that the intrinsic single-particle cross sections calculated by the DWBA

TABLE VII. Optical parameters used in the DWBA calculation.

Parameter	Deuteron	Proton
V (MeV)	104.0	53.0
$r_0=r_c$ (F)	1.15	1.25
a (F)	0.81	0.65
W' (MeV)	54.0	71.0
r_0' (F)	1.34	1.25
a' (F)	0.68	0.47
Lower cutoff	0.0	0.0

[23] The intrinsic states are described by a symbol of the form $(Nn_z\Lambda K\pi)$, where N, n_z, and Λ are the asymptotic quantum numbers, K is the projection of the total angular momentum on the symmetry axis, and π is the parity.
[24] R. H. Bassel, R. M. Drisko, and G. R. Satchler, Oak Ridge National Laboratory Report ORNL-3240 (UC-34-Physics), (unpublished).
[25] F. G. Perey, Phys. Rev. **131**, 745 (1963); C. M. Perey and F. G. Perey, Phys. Rev. **132**, 755 (1963).

code should be reliable. At 60° scattering angle, the intrinsic single-particle cross sections given by the DWBA code were 0.475, 0.145, and 0.0162 mb/sr. Before this set of ϕ_l were used in the cross-section calculation, they were multiplied by the factor 1.5 to compensate for the unrealistic "zero-range approximation" used by the DWBA code. Table VIII lists the wave functions, excitation energies, and differential cross sections (with band mixing) calculated for W^{183} by use of the parameters discussed above. The principal parameters used in the calculation are given in Table IX.

TABLE VIII. Excitation energies and wave functions calculated for W^{183}, W^{185}, and W^{187} together with the calculated differential cross sections for exciting these levels in the present (d,p) reactions at 60° scattering angle.

J	K	E (keV)	Wave function $a_{K=1/2}$	$a_{K=3/2}$	$a_{K=7/2}$	$d\sigma/d\Omega$ with band mixing (mb/sr)
			W^{183}			
$\frac{1}{2}$	$\frac{1}{2}$	0.0	1.00	0.0	0.0	0.005
$\frac{3}{2}$	$\frac{1}{2}$	46.31	0.971	0.239	0.0	0.47
$\frac{3}{2}$	$\frac{3}{2}$	208.68	0.239	−0.971	0.0	0.35
$\frac{5}{2}$	$\frac{1}{2}$	99.30	0.941	0.339	0.0	0.29
$\frac{5}{2}$	$\frac{3}{2}$	291.86	0.339	−0.941	0.0	0.15
$\frac{7}{2}$	$\frac{1}{2}$	207.11	0.886	0.464	0.0	0.02
$\frac{7}{2}$	$\frac{3}{2}$	412.06	0.464	−0.886	0.0	0.08
$\frac{7}{2}$	$\frac{7}{2}$	453.08	0.0	0.0	1.0	0.41
$\frac{9}{2}$	$\frac{1}{2}$	308.75	0.867	0.497	0.0	0.008
$\frac{9}{2}$	$\frac{3}{2}$	555.53	0.497	−0.867	0.0	0.001
$\frac{9}{2}$	$\frac{7}{2}$	588.08	0.0	0.0	1.0	0.003
$\frac{11}{2}$	$\frac{1}{2}$	477.28	0.800	0.599	0.0	0.00001
$\frac{11}{2}$	$\frac{3}{2}$	745.30	0.599	−0.800	0.0	0.0005
$\frac{11}{2}$	$\frac{7}{2}$	753.08	0.0	0.0	1.0	0.0006
			W^{185}			
$\frac{1}{2}$	$\frac{1}{2}$	13.6	1.00	0.0	0.0	0.005
$\frac{3}{2}$	$\frac{1}{2}$	86.5	0.891	−0.454	0.0	0.81
$\frac{3}{2}$	$\frac{3}{2}$	0.0	0.454	0.891	0.0	0.00005
$\frac{5}{2}$	$\frac{1}{2}$	184.2	0.846	−0.534	0.0	0.0008
$\frac{5}{2}$	$\frac{3}{2}$	57.7	0.534	0.846	0.0	0.44
$\frac{7}{2}$	$\frac{1}{2}$	325.4	0.849	−0.529	0.0	0.09
$\frac{7}{2}$	$\frac{3}{2}$	151.2	0.529	0.849	0.0	0.001
$\frac{7}{2}$	$\frac{7}{2}$	237.0	0.0	0.0	1.0	0.41
$\frac{9}{2}$	$\frac{1}{2}$	485.5	0.833	−0.553	0.0	0.00008
$\frac{9}{2}$	$\frac{3}{2}$	270.9	0.553	0.833	0.0	0.009
$\frac{9}{2}$	$\frac{7}{2}$	391.7	0.0	0.0	1.0	0.003
			W^{187}			
$\frac{1}{2}$	$\frac{1}{2}$	149.0	1.0	0.0	0.0	0.005
$\frac{3}{2}$	$\frac{1}{2}$	205.4	0.994	−0.110	0.0	0.72
$\frac{3}{2}$	$\frac{3}{2}$	0.0	0.110	0.994	0.0	0.09
$\frac{5}{2}$	$\frac{1}{2}$	303.4	0.986	−0.165	0.0	0.08
$\frac{5}{2}$	$\frac{3}{2}$	77.9	0.166	0.986	0.0	0.36
$\frac{7}{2}$	$\frac{1}{2}$	433.8	0.978	−0.209	0.0	0.08
$\frac{7}{2}$	$\frac{3}{2}$	187.5	0.209	0.978	0.0	0.02
$\frac{7}{2}$	$\frac{7}{2}$	351.0	0.0	0.0	1.0	0.41

The theoretical and experimental spectra obtained at 60° scattering angle for the $W^{182}(d,p)W^{183}$ reaction are presented in Fig. 9. This figure shows three different theoretical spectra for W^{183}: (1) a spectrum without band mixing, (2) a spectrum with band mixing, and (3) a spectrum with band mixing and with a correction for the effects of pairing correlations.[13] (In calculating the spectrum with the pairing, the occupation probability $U^2=0.76$ was used for the $[510\frac{1}{2}^-]$ intrinsic state, 0.89 for the $[512\frac{3}{2}^-]$, and 0.92 for the $[503\frac{7}{2}^-]$—the values found for W^{183} by Yoshida.[10]) The spectrum at the top of Fig. 9 has been calculated without band mixing and shows considerable disagreement with the experimental spectrum. The cross sections for the 99- and 209-keV levels are too small, whereas the cross sections for the 46- and 292-keV level are much too large. When the band mixing is added (the middle two spectra) the relative cross sections are in better agreement with the experimental cross sections. It seems clear from the cross-section information alone that considerable band mixing is taking place between the $[510\frac{1}{2}^-]$ and $[512\frac{3}{2}^-]$ intrinsic states in W^{183}. The spectrum calculated with band mixing but without pairing agrees fairly well with the experimental spectrum except that the absolute cross sections are too large. The addition of the pairing seems to correct for this. (Further discussion of the correspondence between theoretical and experimental absolute cross sections appears in Ref. 15.) It is not clear that the agreement with the pairing is really any better than without the pairing since the pairing effects have been calculated in an inconsistent way. The analysis of both Kerman[8] and Brockmeier *et al.*[9] do not include pairing effects explicitly. Consequently, the rotational and mixing parameters which they obtain are only effective parameters. Adding the pairing effects at the end, as has been done above, probably does not give completely reliable results for the cross sections.

TABLE IX. The principal parameters used in the calculation of the excitation energies and differential cross sections.

Parameter	W^{183}	W^{185}	W^{187}
$E^0_{K=1/2}$ (MeV)	0.0	0.0	0.146
$E^0_{K=3/2}$ (MeV)	0.19676	0.003	0.0
$E^0_{K=7/2}$ (MeV)	0.45041	0.227	0.3505
$A_{K=1/2}$ (MeV)	0.01585	0.01713	0.01842
$A_{K=3/2}$ (MeV)	0.01405	0.01518	0.01632
$A_{K=7/2}$ (MeV)	0.0150	0.01621	0.01742
$a_{K=1/2}$	0.1684	0.0717	−0.025
$\langle J_- \rangle$	1.4537	1.25	0.75

Two of the weak levels in the experimental spectrum for W^{183} (levels No. 0 and 5) have theoretical cross sections which are a factor of two or three smaller than the observed cross sections. As given in Tables I and VIII, the observed cross section of the W^{183} ground state is 0.015 mb/sr whereas the theoretical cross section is 0.008 mb/sr. In addition, level No. 5, the 309-keV state, has an observed cross section about 0.02 mb/sr and a calculated cross section of 0.008 mb/sr. At the same time, the theoretical and experimental cross sections for the strongly excited state are in fairly good agreement. This discrepancy between the calculated and

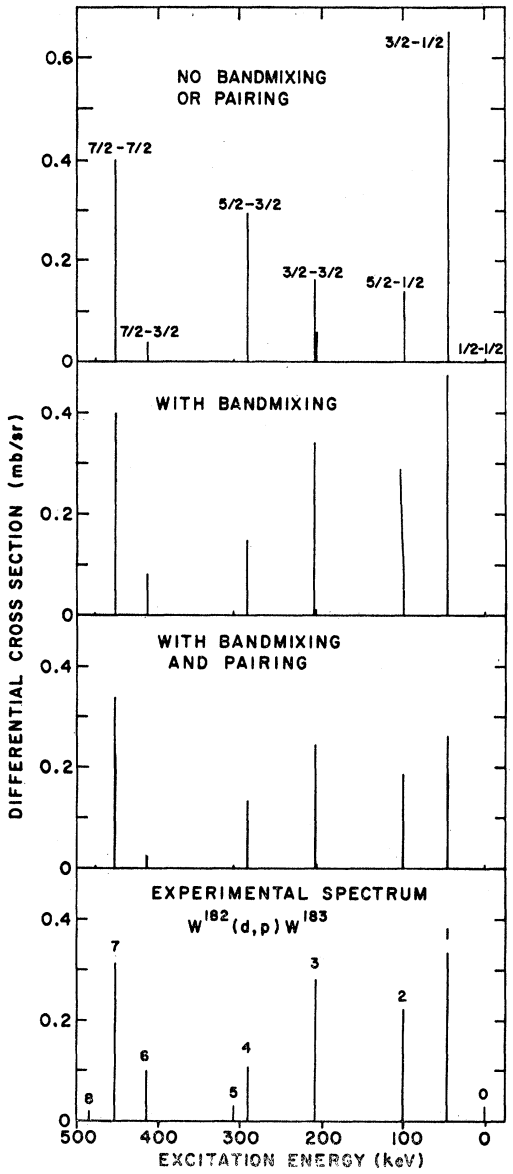

FIG. 9. Comparison of calculated and experimental spectra from the $W^{182}(d,p)W^{183}$ reaction at 60°. Theoretical spectra with and without band mixing as well as without the effects of pairing are shown. The states in one of the calculated spectra are labeled with the symbol J-K which specifies the total angular momentum J and its projection K on the symmetry axis.

experimental cross sections for the weak levels is not surprising since the cross sections of weakly excited levels may have significant contributions from reaction mechanisms other than deuteron stripping. Inelastic scattering effects[12] (coupled-channel effects), for example, may make a major contribution to the ground-state cross section.

In view of the above, it may be that the 484-keV level in W^{183} (level No. 8) is the $J=11/2$ level in the $K=\frac{1}{2}$ rotational band, even though the theoretical cross section for this level is 0.00001 mb/sr, 4 orders of magnitude lower in cross section than the observed cross section of about 0.01 mb/sr. On the other hand, the excitation energy calculated with Kerman's parameters for this same level is 477.28 keV (Table VIII) which is somewhat beyond the energy allowed by the experimental uncertainty in the measured energy of the 484-keV level. This level may arise from other Nilsson intrinsic states, possibly the $[651\frac{1}{2}^+]$ or $[505\frac{9}{2}^-]$ states (as may be inferred from Fig. 13 and the related discussion).

The good agreement obtained between the strongly excited levels in the experimental spectrum and the theoretical spectrum including band mixing is a favorable indication that this method may enable one to identify the various low-lying levels in W^{185} and W^{187}.

On the basis of a one-particle theory, the $[510\frac{1}{2}^-]$ intrinsic state is filled in W^{185}, and both the $[510\frac{1}{2}^-]$ and $[512\frac{3}{2}^-]$ intrinsic states are filled in W^{187}. Residual pairing correlations, however, alter this situation and allow the various intrinsic states to be filled or unfilled in varying degrees. The pairing theory treats intrinsic states as one-quasiparticle states which, in a stripping reaction, behave as before except that the probability of capturing a neutron now depends on the occupation probability U^2. To keep the calculations simple, pairing effects were ignored in the calculation of the W^{185} and W^{187} spectra, and both hole-like and particle-like intrinsic states were treated alike. Of course, the U^2 correction should really be built into the cross section; but this would greatly increase the complexity of the calculations, especially when band mixing is involved.

The spectra for W^{185} and W^{187} were calculated with the same computer code, and initially with the same parameters, as used for W^{183}—except for the parameters which controlled the energy of the intrinsic states. The initial choice of the positions of the intrinsic states was guided by the angular-distribution data which identified the $l=1$ transitions leading to states in W^{185} and W^{187}. These first calculations gave cross sections which corresponded quite closely to the observed cross sections. This suggested that the identification of intrinsic states on the basis of the angular-distribution data was correct. The subsequent calculation concentrated on fitting the excitation energies of the observed levels in W^{185} and W^{187} as well as possible by adjusting the various parameters of the three intrinsic states. Since there are fewer observed levels than parameters, a constraint was imposed on the parameters by keeping the moments of inertia for the $K=\frac{1}{2}$ and $K=\frac{3}{2}$ states in the same proportion as Kerman had found for W^{183}. The fitting is not as reliable for W^{185} as for W^{187} since the number of states observed is one less in W^{185}. The missing state (presumably the $J=\frac{5}{2}$, $K=\frac{1}{2}$ state) probably is too weak to have been observed. As a consequence, the moments of inertia and decoupling parameter for W^{185} could not be accurately determined. In the final calculation of W^{185}, the adopted values of these quantities are the averages

of those for W^{183} and W^{187}. However, in the W^{185} calculation the relative positions of the intrinsic states and the mixing coefficient $\langle J_- \rangle$ were left as free parameters and were empirically adjusted for the best fit. The parameters of these best fits for W^{185} and W^{187} are given in Table IX. No uniqueness can be claimed for the set of parameters for W^{185} and W^{187}. Table VIII lists the excitation energies, wave functions, and differential cross sections calculated for the various levels in W^{185} and W^{187}. The spectra for W^{185} and W^{187}, calculated both with and without band mixing, are presented in Figs. 10 and 11 together with the experimental spectra observed at 60° scattering angle.

The calculated spectra for W^{185} and W^{187} have been obtained by fitting only the observed excitation energies and without using the magnitude of the differential cross section of one level relative to that of another. Then a comparison of the theoretical and experimental cross sections serves as a test of the spin and orbital assignments. The agreement between the calculated and experimental spectra for the $W^{184}(d,p)W^{185}$ and $W^{186}(d,p)W^{187}$ reactions is reasonably good, as can be seen in Figs. 10 and 11. This is a good indication that the spins and intrinsic states have been correctly identified and that the simple rotator-plus-odd-nucleon model is a reasonably valid description of the low-lying states of W^{185} and W^{187}.

One interesting feature of the level structure of W^{185}

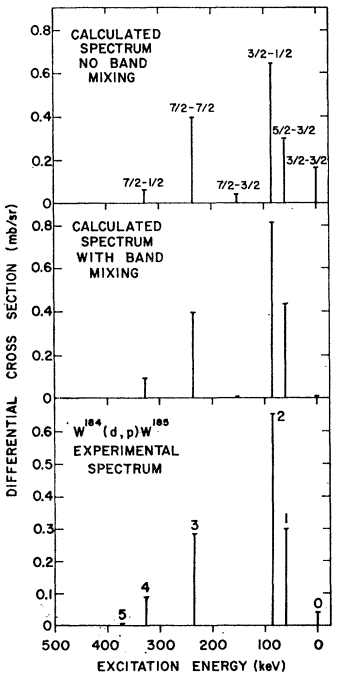

FIG. 10. Comparison of calculated and experimental spectra from the $W^{184}(d,p)W^{185}$ reaction at 60°. Theoretical spectra with and without band mixing are shown. The states in one of the calculated spectra are labeled with the symbol J-K which specifies the total angular momentum J and its projection K on the symmetry axis.

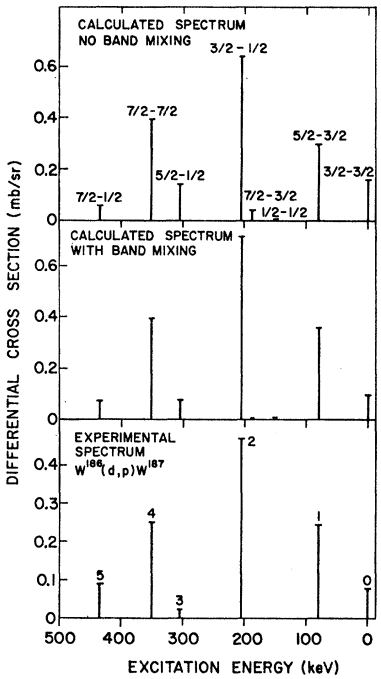

FIG. 11. Comparison of calculated and experimental spectra from the $W^{186}(d,p)W^{187}$ reaction at 60°. Theoretical spectra with and without band mixing are shown. The states in one of the calculated spectra are labeled with the symbol J-K which specifies the total angular momentum J and its projection K on the symmetry axis.

and W^{187} is the behavior of the $J=\frac{5}{2}$, $K=\frac{1}{2}$ and $J=\frac{3}{2}$, $K=\frac{3}{2}$ states as the degree of band mixing is increased. These states appear with a smaller intensity in the calculated spectrum of the $W^{184}(d,p)W^{185}$ reaction than in the (d,p) reaction on W^{186} (Figs. 10 and 11). This difference between the intensities of the calculated spectra of W^{185} and W^{187} results from the greater amount of band mixing in the former. The strength of the weakened states is given to the $J=\frac{5}{2}$, $K=\frac{3}{2}$ and $J=\frac{3}{2}$, $K=\frac{1}{2}$ states with which they admix. The observed spectra (Figs. 2 and 3) seem to exhibit this dependence on band mixing; the counterparts of levels 0 and 3 in the spectrum of the $W^{186}(d,p)W^{187}$ reaction are very weak or unobserved in the $W^{184}(d,p)W^{185}$ spectrum.

The results of this fitting of the low-lying excited state of W^{185} and W^{187} with the rotational model are consistent with the ground-state spins, parities, and moments of inertia found by other methods. The ground-state spin and parity and of both W^{185} and W^{187} are expected[26] to be $J^\pi=\frac{3}{2}^-$ on the basis of the characteristics of the decay of the ground states. This agrees with the spins found by the above fitting procedure. Furthermore, the changes in moments of inertia in going from W^{183} to W^{185} to W^{187} are in agreement with the changes in the moments of inertia obtained from the

[26] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington 25, D. C.), NRC-59-3-125.

measured energies[26] of the first 2^+ states in W^{182}, W^{184}, and W^{186} (0.100, 0.111, and 0.122 MeV, respectively). If Kerman's value $\hbar^2/2\mathcal{I}=0.0158$ MeV for W^{183} is assumed, then the values $\hbar^2/2\mathcal{I}=0.0176$ and 0.0193 MeV for W^{185} and W^{187} are obtained from the energies of the 2^+ states. These moments of inertia are to be compared with the values 0.0171 and 0.0184 MeV found by the fitting procedure used for interpreting the present data.

Higher Excited States of W^{183}, W^{185}, and W^{187}

It would be very interesting to identify the origin of the many highly excited states (other than those discussed in the previous section) which are observed in W^{183}, W^{185}, and W^{187}. In the real nucleus the highly excited states are very complicated, and it is probably not possible to separate them neatly into various types of excitations. However, for the sake of simplicity it is desirable to deal with the various excitations singly in hopes that some features of the observed levels can be explained. The following types of excitations are known to be present at low excitation energy and presumably are still present to some degree in highly excited deformed nuclei. The simplest type of excitation is the excitation of an odd nucleon into the various Nilsson states of the deformed potential. In the strong-coupling limit, these intrinsic excitations can be combined with collective excitations of all the nucleons. The latter can take the form of rotational and/or vibrational motions of the core (the γ and β vibrations). In real nuclei at high excitation energies, the actual state is presumably some complicated admixture of these various excitations. The degree of admixing may not be too great for the first few MeV of excitation. Consequently, one might hope to recognize some features of intrinsic and rotational excitations in the present experimental data. Pure γ and β vibrational states are not expected in the present data, since the (d,p) reaction populates these collective excitations only weakly.

The $W^{182}(d,p)W^{183}$ spectrum expected from the intrinsic and rotational states in W^{183} was calculated on the basis of the simple rotational model. The proton spectrum was calculated for an observation angle of 60° and for a 3-MeV range of excitation energy. To keep things simple, band mixing, decoupling effects for $K=\frac{1}{2}$ bands, and the effects of pairing correlations were ignored. For the states at high excitation energy, the principal effect of omitting the pairing is that the calculated excitation energies of all these states will be too high by about 300 to 500 keV. (This is the amount of shift calculated through the use of the BCS equations, if $\Delta=0.62$ MeV is assumed.)

Nilsson's choice[5] of parameters ($\mu=0.45$, $\kappa=0.05$, $\hbar\omega_0=41A^{-1/3}$ MeV) was used to calculate the location of the various intrinsic states. A deformation of $\eta=4.24$ was used for W^{183}, in accordance with the values given by Mottelson and Nilsson.[27] The same rotational-energy parameter $\hbar^2/2\mathcal{I}=0.015$ MeV was used for each intrinsic state. The intrinsic single-particle cross sections were calculated as a function of the reaction Q value by use of the DWBA direct-interaction code TSALLY[24] with the potentials of Table VII. The calculated spectrum is shown in Fig. 12. In this figure, the calculated cross sections of the various Nilsson intrinsic states are

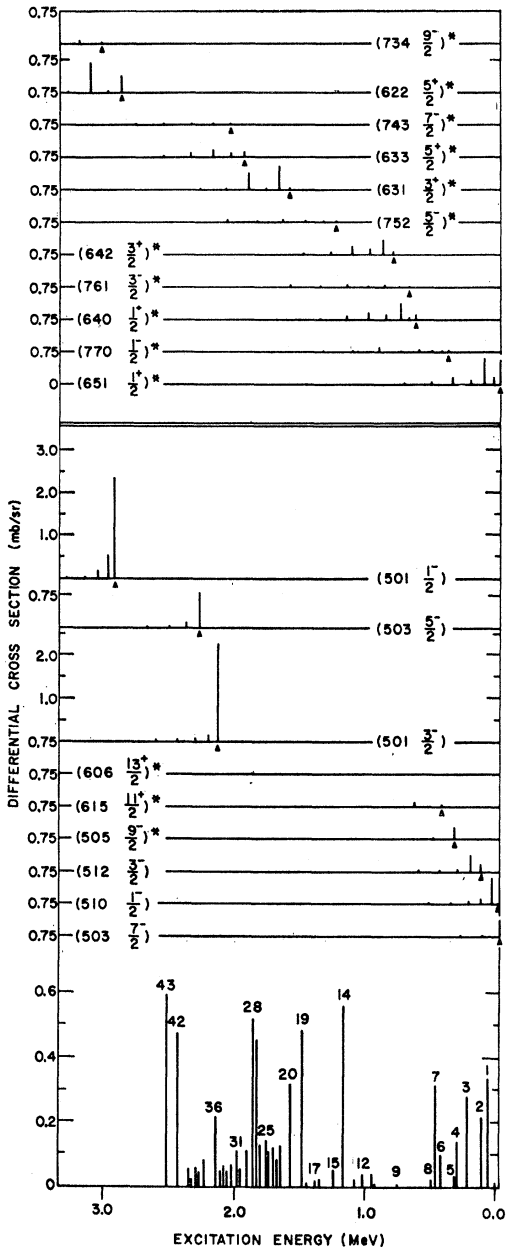

FIG. 12. Theoretical differential cross sections at 60° of the various Nilsson intrinsic states expected in the $W^{182}(d,p)W^{183}$ reaction. The values are plotted against the excitation energy in W^{183}. The rotational levels associated with each Nilsson intrinsic state are also shown. The intrinsic states have small triangles under them. The differential cross sections for some Nilsson states have been plotted five times as large as their actual values. These states are marked with asterisks. The observed spectrum is also given.

[27] B. R. Mottelson and S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat. Fys. Skrifter 1, No. 8 (1959).

plotted against their excitation energies in W^{183}. The rotational band associated with each Nilsson state is also displayed. The Nilsson states are separated by a double line into the group that arise from the $j_{15/2}$, $i_{11/2}$, and $g_{9/2}$ shell-model states above the gap at 126 neutrons and the group which arises from the $p_{1/2}$, $f_{5/2}$, $p_{3/2}$, $i_{13/2}$, and $h_{9/2}$ shell-model states below this gap. Below the calculated spectra and on the same energy scale appears the experimental spectrum at 60° for the $W^{182}(d,p)W^{183}$ reaction. Theoretical spectra of rotational bands with very small cross sections are plotted five times as large as their actual values and marked with asterisks. The lowest energy state of each of rotational band is marked with a small triangle.

There appears to be little correlation between the theoretical and observed spectra in Fig. 12, even with regard to the gross features of the spectra. The $[501\frac{3}{2}^-]$, $[503\frac{5}{2}^-]$, and $[501\frac{1}{2}^-]$ Nilsson states have by far the largest cross sections in the theoretical spectrum. However, it does not appear possible to identify particular groups in the experimental spectrum with these Nilsson states since at least seven strong groups are present at about the right excitation energy. (Note: Because of the neglect of pairing in the calculation, the theoretical energies of the highly excited states are placed 300–500 keV too high in excitation energy.) Even at a few MeV excitation, it appears that some strong interaction is splitting the simple Nilsson states into more complicated types of excitations.

Another observation can be drawn from the theoretical and experimental spectra in Fig. 12. The upper part of the figure shows a number of Nilsson states that arise from shell-model states above the gap at 126 neutrons. Some of these states have energies near the energy of the ground state; yet none of the states have been observed below 0.45-MeV excitation in W^{183} even though some of them have theoretical cross sections large enough to have been seen. In particular, the $[651\frac{1}{2}^+]$ state in the theoretical spectrum falls at about the same energy as the ground state; yet the lowest state that can possibly be identified with it is the state observed at 484 keV in W^{183}.

The detailed level structure of W^{183}, W^{185}, and W^{187} at high excitation energies seems to be greatly different from one nucleus to the next, even though they differ one from the other by only one or two pairs of neutrons. This can be seen in Fig. 13 where the (d,p) spectra showing the levels in these three nuclei are plotted against the same Q-value scale. No common features of the highly excited states seem to be present except for a tendency for a group of strongly excited states to occur near $Q=2.5$ MeV. Possibly these levels are related to the $[501\frac{3}{2}^-]$ Nilsson states since they seem to be $l=1$ transitions (Tables II and III) and are strong groups relatively close to the ground state.

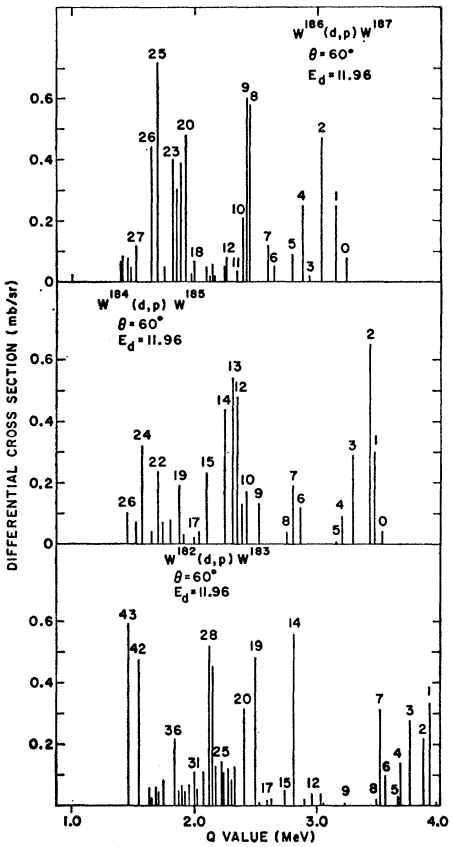

FIG. 13. Experimental spectra of protons produced by the (d,p) reaction on W^{182}, W^{184}, and W^{186} at 60°. These data have been plotted on the same Q-value scale.

These dissimilarities among the highly excited states of W^{183}, W^{185}, and W^{187} are not too surprising since these nuclei are close to the edge of the deformed region where rotational behavior is not as dominant a feature of the nuclear structure as for nuclei near the center of the deformed region. Nevertheless, at low excitation energies the rotational model might be expected to hold quite well. As was demonstrated above, the rotational model does give a good account of the relative differential cross sections for low-lying levels in W^{183} and seems to be nearly as successful in explaining the properties of the lowest energy states in W^{185} and W^{187}.

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