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FAST NEUTRON SCATTERING FROM THE 182, 184, AND 186 ISOTOPES OF TUNGSTEN

by

D. Lister, A. B. Smith,
and C. Dunford

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Available from

Clearinghouse for Federal Scientific and Technical Information
National Bureau of Standards, U. S. Department of Commerce
Springfield, Virginia 22151

Price: Printed Copy \$3.00; Microfiche \$0.65

ANL-7288
Physics (TID-4500)
AEC Research and
Development Report

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439

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H.C. \$ 3.00; MN 65

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and

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January 1967

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FAST NEUTRON SCATTERING FROM THE 182, 184, AND 186 ISOTOPES OF TUNGSTEN

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D. Lister, A. B. Smith,
and C. Dunford

ABSTRACT

The differential cross sections for the elastic and inelastic scattering of fast neutrons from W^{182} , W^{184} , and W^{186} were experimentally determined at incident neutron energy intervals of $\lesssim 25$ keV from 0.3 to 1.5 MeV. The excitation, by inelastic scattering, of states in W^{182} at 102 ± 5 and 327 ± 10 keV; in W^{184} at 110 ± 5 , 360 ± 10 , 901 ± 10 , 1003 ± 10 , and 1120 ± 10 keV; and in W^{186} at 121 ± 5 , 398 ± 10 , 738 ± 10 , 863 ± 10 , 942 ± 10 , and 1035 ± 10 keV was observed. The differential elastic and inelastic scattering cross sections were measured at eight or more angles between 27 and 150° by means of a multiangle, fast time-of-flight system. The resolution was sufficient to resolve most of the scattered neutron groups. The experimental results were interpreted in terms of a deformed optical model, coupled-channel direct interaction, and Hauser-Feshbach theory. Good agreement with measurement was obtained when the effects of resonance width fluctuations and correlations were included.

I. INTRODUCTION

The study of fast neutron scattering from the even-even isotopes of tungsten is of interest from several points of view. Such studies provide information about the neutron-nucleus interaction in a mass region of sizeable but changing nuclear deformation.¹ This information can be used to test the validity of interaction models which quantitatively predict contributions from compound-nucleus and direct interaction processes.² In conjunction with an appropriate model, the experimental results can, under favorable circumstances, be interpreted to obtain spectroscopic information. Such information would be particularly desirable in the case of W^{186} as the excited structure of this nucleus has not been extensively studied.³ From the practical standpoint, a good knowledge of elastic and inelastic neutron scattering from tungsten is useful as this metal finds application in high-temperature nuclear systems.

A number of experimental studies of the excited structure of the even isotopes of tungsten have been reported. Most of these have dealt with the electromagnetic decay of the excited nuclei following beta emission³⁻⁸ and Coulomb excitation.^{3,9-11} (The references cited here are representative; see also references contained therein.) In addition, experimental (d,p) studies¹² of W^{184} and (α ,xn) reaction studies¹³ of W^{182} have been reported. Many of the properties of W^{182} , W^{184} , and W^{186} have been successfully described by the collective model.¹⁴⁻¹⁷ Each nuclide has an equilibrium nuclear deformation as evidenced by a characteristic rotational-band structure. However, as the mass increases from 182 to 186, the deformation decreases slightly becoming less rigid and, in particular, more "soft" toward γ -vibration.^{18,19}

Previous studies of the interaction of fast neutrons with tungsten have included a number of total cross section measurements pertaining to the natural element and to the separated even isotopes.^{20,21} Gamma rays emitted following inelastic neutron scattering have been observed by several workers, not always with consistent results.²²⁻²⁴ Neutron capture gamma rays have been studied in some detail,²⁵ but the results have not always been easy to interpret spectroscopically. Fast neutron scattering measurements in the incident energy region of $\lesssim 1.5$ MeV have taken several forms. The differential total-neutron-scattering cross section has been measured for natural tungsten.²⁶ Both elastic- and inelastic-scattering cross sections of W^{184} were measured in relative detail at a number of incident neutron energies between 0.3 and 1.5 MeV.²⁷ The present study elaborates on the previously reported measurements of W^{184} and extends the measurements to W^{182} and W^{186} . The experimental results were compared in detail with the predictions of an interaction model based upon a spheroidal optical potential, coupled-channel direct interaction, and Hauser-Feshbach theory.

II. EXPERIMENTAL METHOD

A. Apparatus

The experiments were carried out using the pulsed-beam, fast neutron, time-of-flight technique.²⁸ The apparatus employed was unusual in that it included a multiangle detection system capable of determining scattered neutron time-of-flight distributions at eight angles concurrently.²⁹ The measured laboratory scattering angular interval extended from $\sim 27^\circ$ to $\sim 150^\circ$ in increments of about 15° . A pulsed Van de Graaff accelerator and a magnetic bunching system of the Mobley type³⁰ were used to produce intense nanosecond ion bursts at the neutron-producing targets. Throughout the measurements, the neutron source was the $Li^7(p,n)Be^7$ reaction, with the scattering samples placed approximately 11 cm from the neutron source and at 0° with respect to the incident proton beam. The scattered neutron flight paths were approximately 200 cm. The incident neutron energy spread

varied from 15 to 25 keV, and the scattered neutron resolution was 1-2 nsec/m. These resolutions made it possible to observe inelastic neutron excitation of most individual states in the bombarded nuclei. At most incident neutron energies, the elastically scattered neutron group was resolved from the inelastic neutrons. The detectors were sensitive to neutrons with scattered energies of $\lesssim 200$ keV. However, in this energy region, the detector sensitivities were rapidly varying functions of scattered neutron energy, and thus quantitative measurements of cross sections were confined to scattered neutron energies of $\gtrsim 300$ keV where the experimental sensitivity determinations were felt to be more precise. The absolute sensitivities of the detectors depended upon the experimental configuration. The practical limit of sensitivity was about 4 mb/sr.

The scattering samples were solid right circular cylinders, 2.03 cm in diameter and 2.03 cm high, positioned so that the axis was perpendicular to the scattering plane. They were fabricated by means of powder-metallurgy forming techniques, which gave sample densities approaching the theoretical density of the material. The isotopic abundance of each of three samples is given in Table 1.

Table 1. Isotopic Content of Tungsten Samples

Sample	Isotope				
	<u>180</u>	<u>182</u>	<u>183</u>	<u>184</u>	<u>186</u>
	Isotopic Composition, w/o				
A	<0.05	94.9	1.58	2.39	1.17
B	<0.05	1.38	1.84	93.88	2.89
C	<0.05	0.58	0.41	1.34	97.66

B. Data Reduction

Measurements at each energy were made in a programmed sequence. The initial measurement was a background determination. This was followed by individual measurements of the three tungsten samples and of one or more scattering standards. After the sequence was completed, the incident neutron energy was incremented by a predetermined amount, and the sequence was repeated. The experimental neutron time-of-flight spectra were analyzed for both the yield and the reaction Q-values of the various scattering channels. These quantities were reduced to cross sections relative to the standard cross sections using an extensive off-line digital-computer processing code. This data-processing procedure is described in detail elsewhere.²⁹ The code first computed the neutron detection efficiency of each detector as a function of energy from the observed standard sample scattering data and known standard cross section. Then the code used the results to calculate the differential cross sections for the samples under investigation. For scattered neutron energies of $\lesssim 1.2$ MeV, the standard was the

elastic scattering cross section of carbon.²⁶ Above a scattered neutron energy of ~ 1.2 MeV, a secondary standard scattering cross section, that of zirconium, was employed. The zirconium cross section had been previously determined relative to those of carbon.²⁶ This processing procedure included corrections for angular resolution, attenuation of the incident beam, and multiple scattering. The results quoted throughout this report were derived for samples having the isotopic composition given in Table 1. The primary isotope in each sample was $\geq 94\%$ abundant, with any minor isotope of $\lesssim 2.4\%$ abundance. No correction was made for the presence of minority isotopes. Each elastic scattering angular distribution was fitted by the least-squares method with a Legendre polynomial of form

$$\frac{d\sigma(\theta)}{d\Omega} = (4\pi)^{-1} \sigma_{el} \left[1 + \sum_{i=1}^N \omega_i P_i(\cos \theta) \right], \quad (1)$$

where σ_{el} is the total elastic-scattering cross section, and $\omega_1, \dots, \omega_N$ are expansion coefficients. Both σ_{el} and all ω_i were obtained from the least-squares fitting procedure with the angle, θ , expressed in the laboratory coordinate system. In the fitting procedure, each point was given equal weighting. This procedure was judged to be the best compromise since the measurements were affected by a number of experimental variables, such as resolution, which could not be accurately defined. For most of the fits of Eq. 1, the variance to the experimental values was a minimum for $N = 5$. These fits were accepted as representative of the experimental data. The quality of these descriptions is indicated in Fig. 1, which compares the measured differential elastic cross section for the scattering of 1100-keV neutrons from W^{184} with the curve derived from the fit of Eq. 1. The standard deviations in the ω_i values obtained from the fitting procedure were indicative of the "goodness" of the fitting procedure and did not necessarily describe all the experimental uncertainties. The ω_i values and their uncertainties, $\delta\omega_i$, would, of course, be affected by the choice of weighting as well as by the selection of the angles of observation. The

Fig. 1.

Differential Cross Sections for the Scattering of 1100-keV Neutrons from W^{184} . The measured differential elastic scattering cross section is compared with the $N = 5$ fit of Eq. 1 to the experimental data. The differential cross sections for the inelastic excitation of the 2^+ (110-keV) and 4^+ (360-keV) states are also indicated.

uncertainties in the σ_{e1} values derived from Eq. 1 were estimated to be $\sim 8\%$, including uncertainties in the standard (carbon) cross sections. The above fitting procedure provides a satisfactory analytical description of the measured values and permits a systematic correlation of measurements made at different angles and incident energies. However, the experimental results expressed in the form of Eq. 1 are not necessarily valid beyond the measured angular interval of $\sim 27^\circ$ to $\sim 150^\circ$, nor is there any guarantee that the description will meet all physical criteria. For example, in some cases, extrapolation of the cross sections given in the form of Eq. 1 beyond the measured interval have resulted in negative differential cross sections near 180° .

III. EXPERIMENTAL RESULTS

A. Elastic Neutron Scattering

Neutron scattering measurements were made over the incident energy region of 0.3 to 1.5 MeV during three experimental periods. The results were reproducible within estimated experimental errors. The ω_i , coefficients and σ_{e1} values of Eq. 1 were derived from the data according to the procedure described in Section II. These quantities were then averaged over incident neutron energy intervals of 50 keV. The averaging was carried out point by point so that there was a one-to-one correspondence between the number of measured angular distributions and the averaged quantities. This smoothing procedure insured that the final results corresponded to the same effective incident energy resolution. The results of the experimental measurements averaged in this manner and expressed in the format of Eq. 1 are shown in Figs. 2, 3, and 4 and listed as numerical values in Tables 2, 3, and 4. The quoted uncertainties have the interpretation described in Section II.

At incident energies ≥ 1.25 MeV, the elastically scattered neutron groups could not be clearly resolved from the inelastic components associated with the excitation of the first excited states (excitation energy ~ 0.1 MeV) of these tungsten nuclei. Therefore, at incident neutron energies ≥ 1.25 MeV, the initial σ_{e1} and ω_i values were derived from measurements including both the elastic neutron group and those neutrons associated with the excitation of the first state. The contribution of the inelastic component was then subtracted to give the elastic cross sections of Figs. 2, 3, and 4, and Tables 2, 3, and 4. The inelastic contribution was estimated by an extrapolation of the measured inelastic excitation cross sections to higher incident energies. This extrapolation was guided by the energy dependence of the excitation function as calculated from the statistical compound nucleus model using the Hauser-Feshbach formula. It was further assumed that the inelastic-scattering angular distributions were isotropic. Actually, the pertinent inelastic scattering was moderately anisotropic ($\sim 15\%$) and departed

112-6704

Fig. 2. Differential Elastic Scattering Cross Sections of W^{182} vs Incident Neutron Energy. The format is that of Eq. 1 and the solid lines indicate the results of calculations as described in Section IV of the text.

112-6706

Fig. 3. Differential Elastic Scattering Cross Sections of W^{184} . The notation is as in Fig. 2.

112-6708

Fig. 4. Differential Elastic Scattering Cross Sections of W^{186} . The notation is as in Fig. 2.

Table 2 Elastic Neutron Scattering Cross Sections of W^{182} Expressed in Form of Eq. 1

E_n , (MeV)	σ, b	ω_1	$\delta\omega_1$	ω_2	$\delta\omega_2$	ω_3	$\delta\omega_3$	ω_4	$\delta\omega_4$	ω_5	$\delta\omega_5$
.333	5.730	.802	.017	.378	.021	.083	.035	-.011	.037	-.075	.048
.375	5.600	.879	.025	.526	.033	.154	.048	.002	.054	-.028	.048
.383	5.720	.879	.027	.635	.036	.188	.051	.063	.060	.001	.046
.425	5.640	.873	.030	.683	.039	.175	.059	.054	.065	.000	.065
.431	5.720	.860	.030	.707	.038	.183	.060	.083	.062	.000	.082
.450	5.570	.893	.029	.699	.036	.162	.057	.052	.059	-.003	.077
.475	5.610	.959	.018	.753	.023	.224	.037	.083	.038	.026	.049
.481	5.560	.966	.017	.764	.021	.243	.034	.084	.035	.030	.048
.500	5.450	1.032	.016	.816	.020	.323	.033	.140	.034	.085	.046
.525	5.430	1.045	.014	.884	.018	.351	.029	.140	.029	.048	.037
.531	5.440	1.076	.016	.922	.021	.372	.034	.153	.034	.052	.043
.550	5.190	1.086	.020	.922	.025	.333	.040	.121	.041	.000	.053
.575	5.160	1.097	.018	.968	.023	.322	.036	.100	.037	-.017	.046
.581	5.150	1.131	.019	.991	.025	.325	.039	.116	.039	-.017	.049
.600	4.940	1.167	.021	1.015	.026	.338	.042	.122	.043	-.025	.056
.625	4.990	1.165	.017	1.092	.021	.367	.034	.166	.035	-.041	.045
.631	4.980	1.191	.017	1.116	.022	.377	.036	.183	.036	-.053	.046
.641	4.930	1.192	.017	1.136	.021	.372	.034	.190	.035	-.083	.046
.675	4.950	1.179	.015	1.214	.019	.445	.030	.208	.031	-.042	.038
.683	5.010	1.188	.016	1.232	.021	.438	.034	.205	.034	-.045	.041
.729	4.980	1.222	.022	1.302	.029	.485	.046	.233	.046	-.035	.055
.736	4.960	1.219	.023	1.314	.029	.487	.047	.240	.047	-.043	.058
.761	4.960	1.260	.021	1.368	.026	.557	.043	.283	.043	-.008	.052
.766	4.900	1.269	.022	1.397	.028	.621	.046	.313	.046	.029	.057
.775	4.740	1.294	.014	1.432	.017	.764	.028	.362	.030	.136	.040
.825	4.780	1.391	.024	1.499	.030	.824	.047	.310	.049	.087	.067
.837	4.810	1.423	.031	1.506	.039	.817	.060	.271	.063	.059	.087
.875	4.530	1.323	.022	1.456	.027	.732	.042	.214	.045	.008	.061
.925	4.530	1.400	.032	1.600	.040	.919	.063	.355	.066	.048	.090
.950	4.690	1.492	.042	1.713	.052	1.094	.082	.495	.087	.171	.118
.985	4.610	1.515	.028	1.691	.035	1.044	.055	.415	.057	.146	.077
.993	4.680	1.548	.029	1.717	.036	1.079	.058	.436	.060	.181	.079
1.025	4.490	1.550	.031	1.743	.039	1.045	.062	.432	.063	.111	.083
1.030	4.510	1.568	.030	1.767	.038	1.049	.060	.428	.062	.100	.080
1.037	4.570	1.596	.034	1.795	.042	1.067	.068	.459	.069	.100	.088
1.075	4.530	1.616	.037	1.868	.047	1.178	.075	.516	.077	.154	.098
1.080	4.580	1.644	.038	1.893	.049	1.223	.078	.521	.079	.182	.100
1.087	4.580	1.633	.040	1.919	.051	1.229	.082	.546	.084	.177	.108
1.120	4.570	1.689	.037	1.922	.047	1.253	.077	.512	.077	.177	.096
1.125	4.520	1.710	.038	1.910	.049	1.254	.080	.476	.079	.169	.096
1.133	4.410	1.739	.046	1.902	.059	1.264	.096	.465	.094	.164	.113
1.180	4.490	1.636	.031	1.838	.040	1.111	.064	.399	.066	-.013	.085
1.187	4.560	1.628	.031	1.820	.040	1.079	.065	.386	.067	-.052	.084
1.220	4.570	1.656	.023	1.847	.030	1.107	.048	.419	.050	-.027	.063
1.225	4.640	1.674	.023	1.877	.030	1.127	.049	.431	.051	.016	.063
1.233	4.750	1.679	.022	1.894	.029	1.125	.047	.451	.049	.070	.059
1.279	4.280	1.699	.014	1.912	.019	1.209	.031	.364	.031	.166	.038
1.286	4.100	1.674	.010	1.912	.013	1.232	.020	.301	.021	.243	.027
1.319	4.040	1.639	.020	1.902	.025	1.232	.041	.227	.041	.242	.052
1.325	4.030	1.624	.021	1.928	.027	1.189	.044	.220	.045	.212	.058
1.333	4.060	1.587	.025	1.941	.032	1.174	.051	.201	.052	.196	.066
1.373	4.280	1.614	.034	1.968	.043	1.276	.069	.278	.069	.241	.087
1.381	4.430	1.596	.034	1.977	.043	1.253	.069	.307	.071	.205	.091
1.423	4.410	1.611	.037	2.001	.047	1.316	.076	.370	.076	.213	.096
1.433	4.360	1.592	.035	1.958	.045	1.323	.072	.372	.074	.217	.095

Table 3 Elastic Neutron Scattering Cross Sections of W^{184} Expressed in Form of Eq. 1

E_n , (MeV)	σ, b	ω_1	$\delta\omega_1$	ω_2	$\delta\omega_2$	ω_3	$\delta\omega_3$	ω_4	$\delta\omega_4$	ω_5	$\delta\omega_5$
.333	5.750	.800	.033	.380	.045	.112	.063	-.031	.074	-.024	.056
.375	5.570	.845	.031	.540	.041	.170	.059	.028	.067	-.030	.059
.383	5.640	.822	.021	.640	.029	.175	.039	.105	.048	-.016	.022
.425	5.610	.799	.034	.676	.044	.131	.067	.033	.071	-.029	.077
.431	5.470	.809	.036	.665	.048	.121	.072	-.011	.077	-.024	.079
.450	5.460	.825	.034	.681	.044	.117	.069	-.003	.071	-.032	.091
.475	5.540	.911	.025	.750	.032	.197	.051	.040	.051	.002	.064
.481	5.520	.944	.023	.752	.030	.200	.047	.039	.047	.002	.058
.500	5.370	1.015	.018	.827	.023	.339	.036	.123	.038	.097	.050
.525	5.270	1.032	.022	.890	.028	.378	.045	.113	.046	.089	.059
.531	5.290	1.069	.024	.929	.030	.405	.048	.129	.049	.096	.062
.550	5.010	1.054	.030	.895	.038	.346	.061	.106	.062	.037	.082
.575	5.010	1.061	.028	.947	.035	.336	.057	.097	.058	-.008	.075
.581	5.010	1.104	.028	.973	.036	.355	.057	.117	.058	.007	.074
.600	4.760	1.135	.027	.966	.034	.365	.053	.128	.055	-.006	.074
.625	4.860	1.123	.024	1.048	.030	.388	.048	.168	.049	-.011	.063
.631	4.850	1.153	.022	1.072	.028	.409	.045	.173	.045	-.004	.057
.641	4.760	1.151	.024	1.063	.030	.400	.048	.171	.049	-.029	.064
.675	4.880	1.143	.022	1.189	.028	.475	.045	.195	.044	-.013	.055
.683	4.940	1.169	.021	1.224	.026	.495	.043	.211	.041	-.013	.049
.730	4.830	1.213	.030	1.297	.039	.611	.063	.233	.061	.052	.072
.737	4.890	1.240	.034	1.298	.045	.613	.072	.235	.069	.070	.081
.770	4.840	1.224	.042	1.355	.054	.619	.088	.272	.085	.014	.100
.775	4.800	1.213	.029	1.370	.037	.594	.060	.271	.059	-.032	.071
.783	4.870	1.218	.036	1.378	.046	.564	.074	.270	.072	-.053	.086
.818	4.780	1.280	.042	1.470	.053	.741	.085	.343	.086	.021	.109
.825	4.860	1.301	.049	1.486	.062	.735	.099	.347	.099	.000	.124
.837	4.810	1.331	.036	1.521	.044	.870	.070	.388	.073	.096	.100
.875	4.440	1.239	.022	1.440	.028	.750	.044	.297	.046	.007	.063
.931	4.480	1.375	.038	1.610	.049	.836	.078	.353	.079	-.070	.099
.950	4.540	1.440	.046	1.689	.058	.952	.092	.432	.094	.022	.119
.979	4.450	1.461	.038	1.682	.048	.961	.076	.391	.077	.026	.097
.985	4.530	1.491	.035	1.703	.045	.983	.071	.402	.071	.044	.088
.993	4.440	1.480	.024	1.678	.031	1.033	.049	.397	.050	.101	.065
1.025	4.290	1.507	.019	1.698	.025	1.032	.040	.395	.040	.065	.050
1.030	4.290	1.535	.019	1.723	.025	1.052	.040	.396	.040	.076	.049
1.037	4.170	1.494	.017	1.702	.022	1.022	.035	.388	.036	.050	.046
1.075	4.190	1.554	.022	1.787	.028	1.121	.045	.459	.046	.043	.059
1.080	4.210	1.567	.024	1.815	.030	1.135	.048	.469	.049	.021	.064
1.087	4.170	1.562	.022	1.823	.027	1.166	.044	.475	.045	.044	.061
1.125	4.130	1.596	.026	1.851	.032	1.213	.052	.511	.054	.050	.072
1.130	4.130	1.616	.027	1.856	.034	1.227	.055	.507	.057	.066	.075
1.137	4.080	1.596	.032	1.845	.040	1.219	.064	.501	.066	.063	.088
1.175	3.980	1.601	.057	1.869	.071	1.167	.113	.471	.119	-.022	.159
1.180	3.940	1.571	.065	1.868	.081	1.164	.129	.472	.136	-.032	.183
1.187	3.840	1.564	.073	1.858	.091	1.110	.144	.417	.152	-.092	.205
1.220	3.940	1.690	.059	1.937	.073	1.212	.117	.446	.122	-.008	.162
1.225	4.020	1.726	.051	1.968	.063	1.250	.102	.456	.106	.023	.139
1.233	3.860	1.778	.051	1.985	.063	1.329	.101	.475	.104	.100	.138
1.273	3.950	1.757	.016	2.009	.021	1.357	.034	.429	.034	.200	.041
1.281	3.770	1.710	.012	2.007	.015	1.357	.025	.357	.025	.259	.032
1.323	3.710	1.702	.024	2.020	.031	1.361	.049	.333	.050	.240	.063
1.333	3.750	1.661	.027	2.025	.035	1.278	.056	.302	.056	.206	.072
1.373	3.750	1.768	.023	2.089	.030	1.474	.048	.370	.048	.288	.061
1.381	3.860	1.732	.020	2.080	.026	1.432	.041	.383	.042	.239	.056
1.423	3.950	1.748	.023	2.100	.029	1.504	.047	.416	.047	.248	.059
1.433	3.920	1.697	.025	2.077	.031	1.486	.051	.432	.052	.227	.065
1.473	3.870	1.735	.033	2.083	.042	1.470	.068	.368	.069	.187	.085
1.481	3.760	1.721	.032	2.040	.041	1.459	.067	.337	.068	.163	.086

Table 4 Elastic Neutron Scattering Cross Sections of W^{186} Expressed in Form of Eq.1

E_n , (MeV)	σ, b	ω_1	$\delta\omega_1$	ω_2	$\delta\omega_2$	ω_3	$\delta\omega_3$	ω_4	$\delta\omega_4$	ω_5	$\delta\omega_5$
.325	5.800	.734	.016	.470	.024	.136	.029	.063	.040	.000	.000
.383	5.440	.806	.031	.666	.042	.225	.057	.052	.070	.055	.038
.425	5.570	.822	.030	.722	.039	.231	.059	.033	.065	.065	.066
.431	5.660	.817	.030	.743	.038	.240	.060	.052	.062	.081	.083
.450	5.540	.858	.031	.735	.039	.239	.062	.026	.064	.071	.085
.475	5.570	.927	.024	.792	.030	.322	.048	.068	.049	.089	.063
.481	5.530	.910	.025	.801	.031	.306	.049	.071	.051	.065	.067
.500	5.380	.979	.027	.860	.034	.399	.055	.134	.056	.128	.075
.525	5.270	.984	.015	.923	.019	.413	.031	.117	.031	.082	.040
.531	5.280	1.024	.015	.960	.019	.453	.030	.136	.030	.103	.039
.550	5.050	1.013	.014	.943	.018	.388	.029	.106	.030	.034	.041
.575	5.110	1.036	.010	1.004	.013	.389	.021	.110	.022	.009	.028
.581	5.100	1.023	.011	1.002	.014	.376	.023	.122	.024	.002	.030
.591	5.060	1.076	.014	1.029	.018	.392	.029	.152	.030	.006	.038
.631	5.020	1.097	.031	1.136	.040	.439	.061	.174	.062	.004	.070
.638	5.000	1.123	.037	1.168	.048	.458	.072	.185	.074	.003	.083
.672	4.700	1.167	.042	1.222	.056	.509	.081	.201	.084	.023	.092
.677	4.510	1.168	.037	1.239	.049	.547	.069	.224	.074	.033	.079
.686	4.440	1.220	.044	1.262	.059	.578	.082	.238	.088	.074	.090
.732	4.550	1.208	.033	1.292	.042	.605	.064	.245	.063	.064	.072
.740	4.460	1.192	.035	1.295	.044	.604	.065	.260	.066	.052	.075
.763	4.650	1.183	.028	1.299	.034	.633	.054	.259	.052	.052	.067
.768	4.530	1.196	.033	1.291	.040	.676	.062	.280	.060	.094	.078
.777	4.510	1.230	.044	1.295	.053	.689	.083	.287	.080	.118	.103
.825	4.340	1.250	.026	1.378	.032	.712	.051	.261	.054	.023	.073
.837	4.250	1.270	.026	1.401	.032	.689	.051	.228	.054	.089	.073
.885	4.270	1.323	.035	1.459	.044	.799	.063	.275	.068	.036	.080
.921	4.220	1.403	.055	1.569	.073	.936	.099	.372	.109	.108	.118
.928	4.270	1.461	.069	1.609	.092	1.003	.123	.414	.136	.185	.144
.951	4.230	1.428	.065	1.666	.086	1.059	.121	.484	.131	.156	.150
.989	4.050	1.484	.050	1.722	.067	1.082	.094	.424	.101	.098	.112
.996	4.120	1.501	.036	1.748	.048	1.125	.069	.436	.074	.094	.086
1.026	3.920	1.538	.030	1.741	.040	1.130	.058	.401	.062	.111	.071
1.030	3.920	1.568	.031	1.747	.042	1.142	.060	.387	.064	.122	.072
1.035	3.950	1.590	.035	1.750	.047	1.166	.068	.392	.072	.146	.081
1.042	3.800	1.577	.039	1.736	.051	1.162	.073	.394	.078	.142	.088
1.072	3.910	1.589	.033	1.780	.042	1.189	.066	.431	.068	.115	.086
1.075	3.910	1.604	.034	1.795	.044	1.204	.068	.439	.070	.108	.087
1.081	3.860	1.605	.035	1.797	.045	1.199	.071	.435	.073	.100	.092
1.088	3.860	1.621	.038	1.794	.049	1.200	.076	.432	.079	.081	.097
1.125	3.920	1.633	.042	1.867	.055	1.255	.082	.475	.086	.038	.101
1.131	3.910	1.649	.045	1.871	.059	1.271	.087	.466	.092	.046	.105
1.138	3.870	1.631	.044	1.872	.059	1.245	.083	.454	.090	.005	.103
1.176	4.030	1.721	.033	1.918	.045	1.277	.063	.465	.068	.022	.073
1.182	4.020	1.735	.039	1.913	.052	1.245	.073	.431	.079	.006	.083
1.190	4.170	1.778	.046	1.933	.062	1.245	.087	.434	.094	.021	.097
1.221	4.090	1.804	.026	1.944	.033	1.327	.052	.457	.054	.074	.062
1.226	4.060	1.784	.028	1.945	.036	1.321	.055	.448	.058	.074	.066
1.235	3.990	1.810	.029	1.937	.037	1.349	.057	.450	.059	.106	.068
1.266	3.820	1.798	.024	1.971	.031	1.429	.050	.456	.050	.149	.061
1.275	3.670	1.745	.020	1.952	.026	1.443	.042	.402	.043	.209	.055
1.333	3.630	1.654	.021	1.973	.028	1.422	.045	.323	.046	.209	.057
1.379	3.880	1.694	.027	2.032	.035	1.483	.057	.345	.059	.262	.074
1.386	3.990	1.684	.030	2.019	.038	1.472	.062	.335	.064	.242	.082
1.419	3.960	1.722	.048	2.061	.062	1.500	.101	.401	.101	.233	.123
1.425	3.980	1.689	.050	2.035	.064	1.462	.105	.405	.106	.205	.129
1.433	3.830	1.653	.063	1.997	.080	1.442	.130	.417	.130	.203	.160
1.473	3.760	1.698	.057	2.022	.074	1.444	.120	.384	.119	.150	.143
1.481	3.860	1.729	.065	2.078	.085	1.454	.139	.373	.136	.146	.159

from symmetry about 90° as well. At incident neutron energies of >1.25 MeV, these characteristics probably affected the corrected σ_{el} values by no more than $\sim 3\%$ and the ω_i values by $\lesssim 5\%$. The transition from results of direct measurements of elastic scattering to those corrected for inelastic contributions may have resulted in the slight discontinuities evident in the elastic cross sections near 1.25 MeV.

B. Inelastic Neutron Scattering

The inelastic neutron excitation of states in W^{182} at 102 ± 5 and 327 ± 10 keV; in W^{184} at 110 ± 5 , 360 ± 10 , 901 ± 10 , 1003 ± 10 , and 1120 ± 10 keV; and in W^{186} at 121 ± 5 , 398 ± 10 , 738 ± 10 , 863 ± 10 , 942 ± 10 , and 1035 ± 10 keV was observed. The respective reaction Q -values were determined from the position of the centroids of the peaks in the time-of-flight spectra relative to the centroid of the elastic peak. The time scale was calibrated from the positions of the elastically and the inelastically scattered neutron groups from Fe^{56} ($Q = -0.846$ MeV), Zr^{92} ($Q = -0.930$ MeV), and Zr^{94} ($Q = -0.916$ MeV), and the position of the elastically scattered second neutron group from the $Li^7(p,n)Be^{7*}$ source reaction [$E_x(Be^{7*}) = 0.432$ MeV]. The above values of the excitation energies in the tungsten isotopes were obtained by averaging the results of several measurements made at different incident neutron energies and scattering angles. The quoted uncertainties were based upon the estimated cumulative uncertainties of the measurements. A scattered neutron region corresponding to a reaction Q -value of ~ -0.05 MeV was not clearly defined due to the presence of elastically scattered neutrons originating in the second group from the source reaction. The situation was further complicated by the excitation of the 2^+ state ($Q \sim -0.1$ MeV) by the second source neutron group. The observed inelastic angular distributions were in general nearly isotropic with slight tendencies toward forward scattering of those neutrons associated with the excitation of the first excited states (2^+). A detailed illustration of this effect is shown in Fig. 5. In view of the approximate isotropy and slight,

Fig. 5

Differential Scattering Cross Sections of W^{184} at an Incident Neutron Energy of 0.6 MeV. The measured differential elastic-scattering and differential inelastic scattering cross sections are indicated by the data points. The solid curves represent the results of calculation (see Section IV of text). The dotted line is an "eye guide" following the measured cross sections for the inelastic excitation of the 2^+ (110-keV) state.

112-6710

Fig. 6. Measured Inelastic Excitation Cross Sections of W^{182} . The solid curves indicate the results of theoretical calculations.

stated uncertainties in cross sections are subjective estimates and include uncertainties in the carbon standard cross sections.

112-6707

Fig. 7. Measured Inelastic Excitation Cross Sections of W^{184} . The solid curve indicates the results of calculations employing a spheroidal potential and including corrections for resonance width fluctuations and correlations. The dotted-dashed curve indicates the calculated direct interaction component. The dashed curve denotes calculations exclusive of the fluctuation and correlation corrections.

nearly linear, angular dependence of the forward peaking of the inelastic scattering angular distributions, it was felt valid to average the differential inelastic cross sections measured at separate angles and multiply by 4π to obtain individual inelastic excitation cross sections. The uncertainty in any inelastic excitation cross section introduced by this procedure was conservatively estimated to be $\pm 10\%$. All the measured values were corrected for multiple scattering, angular resolution, and the effect of incident beam attenuation within the samples and were normalized relative to the known cross sections of the carbon standard. The resulting individual inelastic excitation cross sections of W^{182} , W^{184} , and W^{186} are given in Figs. 6, 7, and 8 and Tables 5, 6, and 7, respectively. The

112-6705

Fig. 8. Measured Inelastic Excitation Cross Sections of W^{186} . The curves indicate the results of theoretical calculations.

Table 5 Inelastic Neutron Scattering Cross Sections of W-182

$Q = -0.102 \pm 0.005 \text{ MeV}$			$Q = -0.327 \pm 0.010 \text{ MeV}$		
$E_n, \text{ MeV}^{(a)}$	σ, b	$\delta\sigma, b$	$E_n, \text{ MeV}^{(a)}$	σ, b	$\delta\sigma, b$
.345	.770	.200	.650	.200	.050
.350	.970	.150	.700	.245	.056
.400	1.270	.150	.700	.180	.050
.425	1.323	.198	.745	.238	.050
.450	1.270	.200	.750	.264	.059
.450	1.579	.236	.750	.243	.050
.475	1.446	.216	.800	.291	.045
.500	1.322	.120	.800	.271	.050
.500	1.514	.181	.850	.326	.049
.525	1.521	.182	.850	.273	.050
.550	1.462	.120	.900	.392	.058
.550	1.602	.192	.900	.302	.050
.575	1.639	.196	.950	.375	.056
.600	1.600	.120	1.000	.396	.059
.600	1.663	.199	1.000	.370	.050
.625	1.615	.193	1.050	.360	.054
.650	1.615	.120	1.050	.330	.070
.650	1.590	.190	1.100	.473	.071
.700	1.730	.120	1.100	.360	.070
.700	1.721	.206	1.150	.401	.070
.750	1.720	.120	1.150	.459	.068
.750	1.708	.120	1.200	.497	.074
.750	1.717	.206	1.200	.412	.070
.800	1.700	.120	1.205	.448	.100
.800	1.703	.204	1.250	.526	.078
.850	1.723	.120	1.250	.403	.080
.850	1.764	.211	1.300	.425	.080
.900	1.862	.223	1.300	.503	.075
.950	1.712	.205	1.305	.540	.150
1.000	1.590	.120	1.350	.551	.082
1.000	1.805	.216	1.350	.503	.090
1.050	1.909	.160	1.400	.471	.090
1.050	1.904	.228	1.450	.438	.090
1.100	1.761	.176	1.400	.568	.085
1.100	1.869	.224	1.405	.445	.100
1.150	1.721	.192	1.450	.486	.072
1.150	1.879	.225	1.495	.442	.090
1.193	1.560	.184	1.500	.533	.079
1.200	1.413	.224	1.500	.383	.090
1.205	1.607	.240	1.550	.441	.066
1.250	1.336	.256			

^a Incident Neutron Resolution $\pm 10 \text{ keV}$

Table 6 Inelastic Neutron Scattering Cross Sections of W-184

Q = -0.110 MeV $\pm$ 0.005 MeV			Q = -0.360 $\pm$ 0.010 MeV			Q = -0.901 $\pm$ 0.010 MeV		
E _n , MeV ^(a)	σ , b	$\delta\sigma$, b	E _n , MeV ^(a)	σ , b	$\delta\sigma$, b	E _n , MeV ^(a)	σ , b	$\delta\sigma$, b
.345	.820	.150	.695	.120	.050	1.200	.351	.050
.395	.950	.180	.700	.175	.060	1.250	.234	.060
.400	.980	.150	.700	.248	.037	1.250	.346	.051
.400	1.384	.207	.745	.240	.050	1.295	.278	.070
.425	1.139	.163	.750	.249	.037	1.300	.200	.060
.445	1.221	.200	.755	.193	.050	1.305	.301	.050
.450	1.020	.150	.795	.213	.050	1.350	.302	.070
.450	1.526	.228	.800	.200	.060	1.350	.331	.049
.475	1.403	.210	.800	.242	.036	1.395	.253	.070
.495	1.306	.150	.845	.259	.050	1.400	.350	.060
.500	1.340	.150	.850	.290	.043	1.400	.344	.051
.500	1.460	.218	.900	.350	.100	1.405	.314	.050
.525	1.427	.214	.900	.340	.051	1.450	.256	.070
.545	1.343	.150	.945	.291	.050	1.450	.341	.051
.550	1.370	.100	.950	.307	.046	1.495	.260	.070
.550	1.502	.225	.995	.321	.050	1.500	.356	.053
.575	1.582	.237	1.000	.290	.080	1.500	.320	.060
.595	1.544	.150	1.000	.336	.050	1.505	.263	.040
.600	1.460	.100	1.045	.271	.050	1.550	.343	.051
.600	1.559	.233	1.050	.260	.060	1.550	.291	.043
.625	1.421	.213	1.050	.322	.048	1.600	.261	.031
.645	1.544	.150	1.095	.296	.060	1.600	.177	.026
.650	1.590	.120	1.100	.330	.080			
.650	1.555	.233	1.100	.359	.053			
.695	1.510	.150	1.145	.284	.060			
.700	1.790	.100	1.150	.300	.100			
.700	1.659	.248	1.150	.357	.053			
.745	1.720	.150	1.195	.294	.060			
.750	1.700	.160	1.200	.410	.080			
.750	1.698	.254	1.200	.303	.045			
.755	1.737	.150	1.205	.326	.050			
.795	1.640	.150	1.245	.295	.070			
.800	1.700	.120	1.250	.400	.060			
.800	1.597	.239	1.250	.336	.050			
.845	1.627	.150	1.295	.306	.070			
.850	1.750	.170	1.300	.350	.080			
.850	1.679	.251	1.300	.361	.054			
.900	1.820	.130	1.300	.346	.051			
.900	1.768	.265	1.305	.334	.050			
.945	1.630	.150	1.345	.335	.070			
.950	1.620	.180	1.350	.380	.070			
.950	1.625	.243	1.350	.339	.050			
.995	1.600	.150	1.395	.319	.070			
1.000	1.720	.130	1.400	.380	.070			
1.000	1.661	.249	1.400	.310	.046			
1.045	1.681	.180	1.445	.315	.070			
1.050	1.590	.100	1.450	.400	.070			
1.050	1.581	.237	1.450	.346	.052			
1.095	1.622	.200	1.495	.272	.070			
1.100	1.640	.130	1.500	.390	.070			
1.145	1.416	.200	1.500	.316	.047			
1.150	1.420	.150	1.505	.315	.070			
1.150	1.626	.243	1.550	.299	.044			
1.193	1.280	.180						
1.200	1.655	.248						
1.200	1.310	.220						
1.200	1.500	.180						
1.205	1.510	.300						
1.245	1.256	.250						
1.250	1.460	.200						
1.300	1.360	.150						
1.350	1.220	.150						
1.400	1.520	.200						
1.450	1.040	.180						
1.500	1.300	.220						

Q = -1.003 $\pm$ 0.010 MeV		
E _n , MeV ^(a)	σ , b	$\delta\sigma$, b
1.300	.364	.050
1.350	.263	.070
1.395	.238	.070
1.400	.281	.042
1.400	.310	.070
1.405	.326	.050
1.450	.291	.043
1.450	.242	.070
1.495	.260	.070
1.500	.355	.053
1.500	.300	.070
1.505	.289	.050

Q = -1.120 $\pm$ 0.010 MeV		
E _n , MeV ^(a)	σ , b	$\delta\sigma$, b
1.400	.150	.080
1.450	.337	.050
1.495	.353	.070
1.500	.468	.070
1.500	.400	.050
1.505	.402	.080
1.550	.414	.062

^a Incident energy resolution ± 10 keV

Table 7 Inelastic Neutron Scattering Cross Sections of W-186

Q = -0.121 ± 0.005 MeV			Q = -0.398 ± 0.010 MeV			Q = -0.863 ± 0.010 MeV		
E _n , MeV ^(a)	σ, b	δσ, b	E _n , MeV ^(a)	σ, b	δσ, b	E _n , MeV ^(a)	σ, b	δσ, b
.350	.600	.200	.750	.223	.033	1.205	.351	.050
.400	1.010	.120	.750	.141	.050	1.250	.343	.051
.400	1.453	.217	.800	.214	.032	1.250	.276	.080
.425	.898	.134	.800	.170	.050	1.300	.375	.056
.450	1.080	.150	.850	.270	.040	1.300	.266	.080
.450	1.448	.217	.900	.235	.035	1.305	.477	.070
.475	1.228	.184	.900	.209	.050	1.350	.358	.053
.500	1.290	.150	.950	.274	.041	1.350	.292	.080
.500	1.458	.218	.950	.272	.050	1.400	.383	.057
.525	1.366	.204	1.000	.264	.039	1.400	.295	.080
.550	1.235	.150	1.000	.222	.050	1.405	.301	.060
.550	1.413	.211	1.050	.255	.038	1.450	.314	.047
.575	1.407	.211	1.050	.225	.050	1.450	.302	.080
.600	1.468	.150	1.100	.267	.040	1.500	.348	.052
.600	1.494	.224	1.100	.208	.050	1.500	.287	.080
.650	1.494	.150	1.150	.237	.035	1.505	.305	.050
.650	1.525	.228	1.150	.175	.050	1.550	.290	.043
.655	1.510	.120	1.200	.230	.034	1.600	.289	.043
.700	1.491	.150	1.200	.203	.050	Q = -0.942 ± 0.010 MeV		
.700	1.604	.240	1.205	.238	.050	E _n , MeV ^(a)	σ, b	δσ, b
.705	1.450	.120	1.250	.260	.039	1.300	.308	.046
.750	1.585	.150	1.250	.195	.050	1.305	.339	.070
.750	1.585	.237	1.300	.279	.041	1.350	.217	.032
.755	1.440	.120	1.300	.208	.050	1.350	.171	.060
.800	1.528	.150	1.350	.253	.037	1.400	.242	.036
.800	1.429	.214	1.305	.339	.070	1.400	.182	.060
.805	1.436	.120	1.350	.221	.050	1.405	.238	.050
.850	1.437	.215	1.400	.300	.045	1.450	.257	.038
.855	1.409	.110	1.400	.242	.060	1.450	.266	.090
.900	1.521	.150	1.450	.153	.023	1.500	.269	.040
.900	1.529	.229	1.450	.181	.070	1.500	.200	.070
.950	1.397	.150	1.495	.245	.060	1.505	.176	.040
.950	1.448	.217	1.500	.196	.029	1.550	.208	.031
.955	1.454	.120	1.500	.247	.070	1.600	.256	.038
.955	1.410	.120	Q = -0.738 ± 0.010 MeV			Q = -1.035 ± 0.010 MeV		
1.000	1.320	.150	E _n , MeV ^(a)	σ, b	δσ, b	E _n , MeV ^(a)	σ, b	δσ, b
1.000	1.305	.195	1.050	.332	.080	1.400	.373	.056
1.005	1.470	.120	1.100	.398	.059	1.400	.289	.070
1.005	1.546	.125	1.100	.334	.080	1.405	.451	.080
1.050	1.302	.195	1.150	.443	.066	1.450	.396	.059
1.055	1.426	.140	1.150	.304	.080	1.450	.296	.070
1.055	1.370	.110	1.200	.411	.061	1.500	.370	.055
1.100	1.321	.140	1.200	.298	.070	1.500	.305	.070
1.100	1.227	.184	1.205	.320	.050	1.505	.389	.050
1.105	1.148	.100	1.250	.354	.053	1.550	.378	.056
1.105	1.200	.100	1.250	.349	.090	1.600	.332	.049
1.105	1.200	.100	1.300	.370	.055			
1.150	1.206	.150	1.300	.291	.070			
1.150	1.200	.180	1.350	.335	.050			
1.155	1.110	.100	1.350	.316	.070			
1.193	1.090	.200	1.400	.377	.056			
1.195	1.117	.200	1.400	.291	.070			
1.200	1.051	.150	1.405	.339	.080			
1.200	1.243	.186	1.450	.322	.048			
1.205	1.070	.100	1.450	.317	.070			
1.205	1.133	.100	1.500	.312	.046			
1.250	1.092	.170	1.500	.321	.070			
1.255	1.061	.100	1.505	.295	.050			
1.255	1.000	.100	1.550	.315	.047			
1.300	1.077	.200						

a) Incident neutron energy resolution
± 10 keV

a) Incident neutron energy resolution
+ 10 keV

IV. THEORETICAL CALCULATIONS

A. Basic Concepts

The experimental elastic and inelastic neutron scattering results were compared with those of calculations based upon an optical model employing a spheroidal nuclear potential.³¹ The calculations considered both statistical compound nucleus (CN) and direct interaction (DI) processes. The DI contribution was determined from a coupled-channel calculation assuming strong coupling between the ground state (0^+) and the strongly excited first rotational level (2^+). The nucleon-nucleus potential was assumed to be local and to have the form

$$V(\underline{r}) = V_0(r) - \beta R_0 (4\pi/5)^{1/2} \cdot \frac{dV_0}{dr} \sum_m Y_2^{m*}(\underline{\Omega}_1) Y_2^m(\underline{\Omega}), \quad (2)$$

where

$\underline{r}$ = relative position vector between the respective centers of mass of the nucleus and neutron,

V_0 = a spherical optical potential,

β = nuclear deformation parameter,

R_0 = radius of an undeformed nucleus having the same mass as the deformed nucleus (incompressibility of nuclear matter is assumed),

$\underline{\Omega}_1$ = orientation of nuclear symmetry axis in laboratory system,

$\underline{\Omega}$ = orientation of $\underline{r}$ in laboratory system,

and

$Y_\ell^m(\underline{\Omega})$ = surface harmonic; $\underline{\Omega} = \theta, \phi$.

The second term on the right-hand side of Eq. 2 describes a static quadrupole deformation of the nucleus. $V(r)$ has nonvanishing matrix elements between the neutron, ground-state wave function and the neutron, first-excited-state wave function as well as between different neutron, first-excited-state wave functions. The incident neutron energies of interest are low enough (≤ 1.5 MeV) to result in large contributions from CN processes. These contributions were calculated using the statistical theory of Wolfenstein³² and Hauser and Feshbach³³ modified as suggested by Moldauer³⁴ to account for the effects of resonance width fluctuations and correlations. The CN cross section for incident neutrons denoted by the subscript n, and for any final system is then given by the following expression:

$$\sigma_{nx} = \frac{\pi}{k^2} \sum g_{\alpha}^J \left\{ \frac{\langle \theta_{\mu\alpha} \rangle \langle \theta_{\mu\beta} \rangle}{\langle \theta_{\mu} \rangle} S_{\alpha\beta} - \frac{\delta_{\alpha\beta}}{4} \cdot Q_{\alpha} \langle \theta_{\mu\alpha} \rangle^2 \right\}, \quad (3)$$

where

g_{α}^J = incident-channel-spin statistical weight factor,

k = incident neutron wave number,

α and β denote all quantum numbers describing any initial channel having an incident neutron and any final channel, respectively,

δ = Kronecker delta function,

$\theta_{\mu} = \sum_{\kappa} \langle \theta_{\mu\kappa} \rangle$; κ = all open channels,

$$S_{\alpha\beta} = \frac{\langle \theta_{\mu\alpha} \theta_{\mu\beta} / \theta_{\mu} \rangle}{\langle \theta_{\mu\alpha} \rangle \langle \theta_{\mu\beta} \rangle / \langle \theta_{\mu} \rangle},$$

and

$$\langle \theta_{\mu\alpha} \rangle = T_{\alpha} + \frac{1}{Q_{\alpha}} \left[1 - (1 - Q_{\alpha} T_{\alpha})^{1/2} \right]^2,$$

where

T_{α} = optical penetrability for channel α ,

and

Q_{α} = a statistical parameter dependent on the properties of the nucleus.

In Eq. 3, the $\langle \rangle$ brackets represent an average over the CN states, which are denumerated by the index μ , and on the right-hand side the sum is over all initial and final-state partial waves. The spherical part of the optical potential employed to obtain values of T_{α} was taken to have a Wood-Saxon real part, a derivative imaginary part with its own median radius and surface diffuseness, and a real Thomas spin-orbit term as follows:

$$V_0(r) = -V_R \{1 + \exp[(r - R)/a]\}^{-1} - 4W \exp[(r - R')/b] \{1 + \exp[(r - R')/b]\}^{-2} \\ - V_{SO} [\hbar/(m_{\pi}c)]^2 \mid r^{-1} d/dr \{1 + \exp[(r - R)/a]\}^{-1} \mid \underline{l} \cdot \underline{\sigma}, \quad (4)$$

where

- V_R = real well depth,
- R = real well radius,
- a = real well diffuseness,
- W = imaginary well depth,
- R' = imaginary well radius,
- b = imaginary well diffuseness,

and

V_{so} = spin-orbit well depth.

The radial shape factor of the quadrupole term of the deformed potential (Eq. 2) was assumed real and given by

$$\frac{dV_0}{dr} = -V_R \frac{d}{dr} \{1 + \exp[(r - R)/a]\}^{-1}. \quad (5)$$

Solutions of the coupled-channel scattering equations were obtained with the computer code 2-PLUS.³¹ This computer code calculates the

Table 8. Optical Potential Parameters Employed in the Deformed Calculations

$V_R = 45.05 - 0.3E, \text{ MeV}$
$R = 1.25A^{1/3}, \text{ fm}$
$a = 0.65, \text{ fm}$
$W = 6.68 + 1.3\sqrt{E}, \text{ MeV}$
$R' = 1.25A^{1/3}, \text{ fm}$
$b = 0.47, \text{ fm}$
$V_{so} = 6.2, \text{ MeV}$

neutron-scattering angular distributions and penetrabilities for the ground state and first excited state using the deformed potential of Eq. 2. The penetrabilities pertaining to the excitation of the second and higher excited states were calculated using the spherical potential only (Eq. 4). The optical potential parameters employed were assumed independent of isotope, and the values used for the deformed-well calculations are given in Table 8. The same parameters were employed for the spherical-well calculations, with the exceptions $V_R =$

44.0 MeV and $W = 8.0$ MeV. The respective compound nucleus cross sections were calculated using a modified form of Moldauer's NEARREX program,³⁵ and the penetrabilities were derived as described above. The calculations were carried out with the Q_α of Eq. 3 equal to unity and included the small contributions due to radiative capture.

B. Comparison of Theory and Experiment

Calculations based on the above concepts were compared with the experimental results. It was felt that the experimental uncertainties did not warrant the inclusion of an isotopic spin term in either real or imaginary potentials, and none was employed. The level structure assumed

for the W^{184} calculations is labeled "model" in Fig. 9. It follows the spectroscopic studies of Harmatz and Handley⁶ and includes states up to an excitation energy of 1.3 MeV. The nuclear deformation parameter, β , was taken equal to 0.24, in agreement with the results of Coulomb excitation measurements.³⁶ All nuclear penetrabilities for the excitation of states above 0.111 MeV (the 2^+ state) were determined from the spherical optical model using the slightly altered potential parameters noted above. The calculated elastic-scattering results are compared with the experimentally observed elastic scattering in Fig. 3. The solid curves of this figure represent the calculated values and are in good agreement with experiment. The calculated compound elastic scattering included the effects of fluctuation and correlation correction terms. These corrections generally increased the elastic cross sections by $\sim 6\%$ and tended to decrease the inelastic cross sections at lower energies ($\sim 25\%$ at 0.3 MeV) and increase them at higher energies ($\sim 20\%$ at 1.5 MeV). This inversion of the correction for the inelastic scattering is due to compensating energy-dependent effects of the resonance width fluctuations and correlations. The calculated inelastic excitation cross sections (solid curves) are compared with experiment in Fig. 7. The fact that the 6^+ state ($E_x \sim 0.75$ MeV, Fig. 9) was not observed is consistent with its calculated cross section (< 2 mb/sr). The solid curve superposed on the measured excitation function for the 1.120-MeV level corresponds to the sum of the calculated contributions from the 1.15-, 1.22-, and 1.287-MeV states of the "model" scheme of Fig. 9.

Fig. 9

Excited States in W^{184} . The structure observed in the present work, that reported in the literature (see Refs. 3, 6, 7, 25, and 39), and the levels assumed in the calculations are shown.

112-7331

Calculated elastic and inelastic differential cross sections are compared with the experimental values for W^{184} at an incident energy of 0.6 MeV in Fig. 5 in the form of angular distributions. These results were representative of those obtained at a number of other incident neutron energies. The calculated elastic distributions were based upon an assumed isotropy for the compound elastic angular distribution. Actually,

detailed Hauser-Feshbach calculations predicted a minimum in the compound elastic component at 90° . Thus the calculated elastic scattering angular distributions should have been slightly larger than the measured values near 90° . However, the effect was not outside the experimental uncertainty. At incident energies larger than ~ 1.2 MeV, the elastic scattering calculations gave somewhat poorer agreement with experiment (Figs. 2, 3, and 4). This was the region of uncertain experimental resolution of elastic and first inelastic components mentioned in Section III.

A feature of the nonspherical optical model was a provision for the direct inelastic excitation of the first (2^+) rotational state. At the incident energies of these experiments (≤ 1.5 MeV), the CN mechanism accounts for most of the cross section for the inelastic excitation of this state in W^{184} . In this energy range, the calculated DI contribution increases with energy to about 20% at incident neutron energies of 1.5 MeV. The DI mechanism leads to an anisotropy in the differential inelastic-scattering cross section. This was observed even at the low incident energy of 0.6 MeV, as indicated in Fig. 5. However, at an incident energy of 5.0 MeV, the same inelastic cross section was calculated to be almost entirely DI and to have a maximum (at 35°) to minimum (at 180°) ratio of 10:1.

The elastic and inelastic cross sections of W^{186} were calculated in a manner analogous to that employed for W^{184} . The level scheme of the "model" in Fig. 10 was employed as a compromise between the structure reported in the Nuclear Data Sheets³ and that obtained from studies of Os^{186} (Ref. 6). The deformation parameter, β , was set equal to 0.23 (Ref. 36). The calculated results (solid curves) are compared with experiment in Figs. 4 and 8. The calculations included correlation and fluctuation corrections.

112-7332

Fig. 10. Excited States in W^{186} . The structure observed in the present work, that reported in Ref. 3, that reported in Ref. 40, and the levels assumed in the calculations are shown.

The calculated W^{182} elastic and inelastic cross sections are compared with experiment in Figs. 2 and 6; β was assumed to be 0.25,³⁶ and the level structure taken to be that given by Harmatz *et al.* (see "model" of Fig. 11).⁵ Experimental values could be obtained only for the excitation of the first two states, 2^+ ($Q = -0.102$ MeV) and 4^+ ($Q = -0.327$ MeV). The excitation of states in W^{182} above 1.2 MeV were not quantitatively observed in this experiment.

112-7330

Fig. 11. Excited States in W^{182} . The structure observed in the present work, that reported in the literature [Refs. 3-5, 13; also B. S. Dzelepov, V. D. Vitman, and N. A. Voinova, Nucl. Phys. **75**, 371 (1966); E. Bashandy, A. H. El-Farrash, and M. S. El-Nesr, Nucl. Phys. **52**, 61 (1964); L. N. Kondrat'ev and E. F. Tret'yakov, Zhur. Eksp. i Teoret. Fiz **46**, 2241 (1964); Soviet Phys.-JETP **19**, 1513 (1964)], and the levels assumed in the calculations are shown.

The theory was used to calculate the strength functions of W^{182} , W^{184} , and W^{186} at an incident neutron energy of 10 keV. The results are given in Table 9 and also compared with the S-wave strength functions deduced from experimental measurements of resolved resonance structure by Russell *et al.*³⁷

Table 9. Calculated Strength Functions of W^{182} , W^{184} , and W^{186}

	W^{182}	W^{184}	W^{186}
S_0 (S-wave)	2.18×10^{-4} (2.2×10^{-4}) ^a	2.24×10^{-4} (2.3×10^{-4})	2.49×10^{-4} (1.6×10^{-4})
S_1 (P-wave)	1.31×10^{-4}	1.36×10^{-4}	1.21×10^{-4}
S_2 (D-wave)	3.21×10^{-4}	3.17×10^{-4}	3.62×10^{-4}

^aNumbers in parentheses are S-wave strength functions derived from the experimental data of Ref. 37.

V. DISCUSSION AND CONCLUSIONS

The results of this work were in reasonable agreement with the reported total cross sections of natural tungsten²⁰ and with the total-scattering angular-distribution measurements of Langsdorf *et al.*²⁶ The observed elastic and inelastic cross sections of W^{184} agreed with those reported by Smith²⁷ within the respective experimental uncertainties. However, the excitation functions of the present work were not compatible with those deduced in studies of the associated gamma rays.^{22,23} The total inelastic neutron-scattering cross sections obtained by summing the individual excitation cross sections determined in these experiments agreed reasonably well with previously reported nonelastic cross sections.^{20,38}

The excited structure of the three even isotopes of tungsten, as reported by a number of authors using a variety of spectroscopic methods, is compared with the results of the present experiments in Figs. 9, 10, and 11. Strong excitation of the first state (2^+ , 0.11 MeV) and weaker excitation of the second state (4^+ , 0.36 MeV) in W^{184} were clearly observed. There was no evidence for a 0^+ state at ~ 0.69 MeV postulated as a result of neutron-capture gamma-ray studies²⁵ and tentatively observed in previous scattering measurements.²⁷ Calculations indicated that such a state should have been observed if present. A state in W^{184} at 1.001 MeV has been assigned a spin parity of 1^+ or 2^+ on the basis of neutron-capture gamma-ray measurements.²⁵ The 1.003-MeV state observed in the present neutron-scattering measurements could be expected to consist of unresolved contributions from the 1.001-MeV state and the well-established 1.007-MeV (3^+) state. However, the calculated excitation function for this state, as shown in Fig. 7, indicates that a single 3^+ level would account for the observed cross section. An additional 1^+ or 2^+ level at this energy would approximately double the cross section. The observed inelastic scattering to a state at 1.120 MeV probably was only partly due to a reported 4^+ , 1.135-MeV state. The measurements suggest this observed scattered-neutron group also contains a component attributable to a level with $J \leq 3$ at about 1.12 MeV, since the observed excitation cross section appreciably exceeded that calculated for the 4^+ configuration alone. A 2^- level has been reported at 1.15 MeV and could be a contributing factor.³⁹

The excited structure of W^{186} derived from these neutron-scattering experiments is compared with the previously reported structure in Fig. 10. The present scattering measurements provided the first direct evidence for the excitation of several states. The measured inelastic neutron cross section associated with the state at 0.942 MeV was in good agreement with the calculated yield curve based on a 4^+ assignment for this state. The observed scattering corresponding to a state at 0.863 MeV substantiated a previous tentative identification of a state having approximately this excitation energy,³ and the calculations

based upon a 3^+ , 6^+ doublet, in analogy to that found⁶ in Os^{186} , agreed reasonably well with experiment. The observed scattering due to the excitation of a state at 1.035 MeV compared well with a postulated 3^- assignment, but the measurements were not sufficiently precise to rule out the previous tentative assignment⁴⁰ of 4^+ .

Only the first two rotational states in W^{182} were clearly observed in these scattering measurements (Fig. 11). The third member of this sequence, 6^+ , was not observed. Its maximum calculated cross section in the energy range of interest was less than 2 mb/sr and would not have been determined in the present work. At the highest incident neutron energies employed (~ 1.5 MeV), there was some evidence for the excitation of states at 1.22 and 1.13 MeV. The former probably corresponds to a 2^+ state as shown in Fig. 11. The 1.13-MeV level probably was not the 8^+ state observed¹³ at 1.138 MeV as its very small calculated cross section would have precluded even marginal observation.

The experimental differential elastic and inelastic neutron-scattering cross sections of W^{182} , W^{184} , and W^{186} in the incident energy interval 0.3 to 1.5 MeV were reasonably well described by coupled-channel optical-model calculations together with the statistical CN model, provided that cognizance was taken of the resonance-width fluctuation and correlation effects.³⁴ This description was found superior to that obtained with the same potential and the uncorrected Hauser-Feshbach formalism. However, for the incident energies of the present experiments, calculations based upon spheroidal and spherical potentials, each including fluctuation potential and correlation corrections, led to essentially equivalent agreement with the experimental results, with the exception of the angular distribution of inelastically scattered neutrons. The validity of the coupled-channel calculation, which allows for direct rotational excitation to the first excited state (2^+), was best revealed in the angular distributions of the inelastically scattered neutrons associated with the excitation of this state. These angular distributions were experimentally well resolved at a number of incident neutron energies and were observed to be slightly peaked in the forward direction, as illustrated in Fig. 5. The same figure shows the calculated distribution (solid curve), including DI contributions, which exhibits the same general shape as the experimental results. As the relative uncertainties associated with the measurements were $\lesssim 10\%$, the relative angular dependence could be meaningfully compared with the calculated results.

The elastic neutron-scattering cross sections calculated using the spheroidal potential were in good agreement with experiment for incident neutron energies of $\lesssim 1.2$ MeV, as illustrated in Figs. 2, 3, and 4. Although at higher incident neutron energies the calculations were less descriptive of the experimental values, the latter were subject to greater uncertainties. An energy-dependent term in the optical potential⁴¹ was included in the above calculations (see parameter values of Table 8). However, the limited

incident neutron energy range of the present measurements was insufficient to specifically verify such an energy dependence. No attempt was made to determine the optical parameters giving a "best fit" to the experimental data. The required detailed search and adjustment, which might have resulted in better agreement with experiment, seemed unwarranted in view of the experimental uncertainties.

The various inelastic excitation cross sections calculated using the spin-and-parity assignments of the "models" of Figs. 9, 10, and 11 were, with several exceptions, in agreement with the measured values (Figs. 6, 7, and 8). The agreement became more qualitative for the excitation of states of energy ≥ 1.0 MeV since not only did the experimental uncertainties increase with incident energy but also the spin-and-parity assignments used in the calculations became more uncertain as the number of exit channels increased. Observed excitation cross sections of the 2^+ , $K = 2$ states in W^{184} (0.901 MeV) and W^{186} (0.738 MeV) are approximately half the calculated values (see Figs. 8 and 9). Electromagnetic transitions involving these levels have been the subject of a number of investigations.^{9,42-44} They probably correspond to the lowest energy γ (lateral)-vibrational states of these nuclei.¹⁸ The discrepancy between calculation and experiment in these cases cannot be removed by the consideration of direct excitation of the vibrational modes as this would only increase the already too large calculated cross sections. It thus appears that further investigation of the statistical theory and inelastic neutron scattering resulting in the excitation of vibrational states would be of value.

In summary, neutron elastic and inelastic scattering cross sections have been measured for $W^{182,184,186}$ in the incident energy range of 0.3 to 1.5 MeV. The results have been successfully analyzed by means of an interaction model containing a spheroidal optical potential, modified Hauser-Feshbach theory, and strong coupling between the ground state and the first excited state.

ACKNOWLEDGMENTS

The authors are indebted to a number of individuals at Atomic International and the Argonne National Laboratory for assisting in various facets of this work. They are also particularly indebted to the National Aeronautics and Space Administration for making available the isotropically separated tungsten samples without which this work would have been impossible.

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