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**FAST-NEUTRON SCATTERING FROM
ELEMENTAL Mo, Sn, Sb, AND Te**

by

A. B. Smith and R. Hayes

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Printed in the United States of America
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-7274
Physics (TID-4500)
AEC Research and
Development Report

CFSTI PRICE

HC \$3.00, MN .65

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439

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Reactor Physics Division

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FAST-NEUTRON SCATTERING FROM ELEMENTAL Mo, Sn, Sb, AND Te*

by

A. B. Smith and R. Hayes

ABSTRACT

Neutrons with incident energies of 0.3 to 1.5 MeV were scattered from elemental Mo, Sn, Sb, and Te. Fast time-of-flight techniques were employed to measure the differential elastic and the differential inelastic scattering cross sections at $\lesssim 25$ -keV increments throughout the incident neutron-energy interval. The inelastic excitation of states was observed: in Mo at 0.20 ± 0.01 , 0.50 ± 0.04 , 0.79 ± 0.06 , and ~ 1.05 MeV; in Sn at ~ 1.2 MeV; in Sb at 0.037 ± 0.003 , 0.16 ± 0.01 , 0.54 ± 0.04 , and ~ 1.1 MeV; and in Te at 0.65 ± 0.02 , 0.75 ± 0.02 , and 0.85 ± 0.02 MeV. The experimental results were compared with calculations based upon a surface-absorption optical potential and the statistical theory of average compound-nucleus cross sections including corrections for width fluctuations. These comparisons were related to the characteristics of the low-energy excited states of the respective nuclei and to the proton shell closure at $Z = 50$.

1. INTRODUCTION

Several experimental studies of the neutron total cross sections and total neutron scattering angular distributions from elements in the region $A = 90$ to 130 and at neutron energies of $\lesssim 1.5$ MeV have been reported.¹⁻³ The relatively few direct determinations of elastic scattering in this mass-energy region have been largely confined to incident energies of ~ 1.0 MeV.⁴⁻⁸ Knowledge of inelastic neutron scattering for the same region of incident energies and target nuclides is derived from only a few measured inelastic neutron scattering excitation functions and limited studies of gamma rays emitted subsequent to the scattering event.⁹⁻¹² This restricted experimental information forms the foundation for comparison with the results of a number of calculations based upon the optical model and the statistical theories of Wolfenstein and Hauser-Feshbach.¹³⁻²⁰ Such

*A short version of this report has been submitted to a professional journal for publication. The present document is inclusive of experimental information in tabular form useful for the applied worker.

comparisons are more significant when extended over a reasonable mass-energy region and when encompassing neutron total cross sections, and differential elastic and differential inelastic neutron scattering processes. Further, sensitivity to spin-orbit forces requires a knowledge of the scattered neutron polarization.^{1,13} The calculations have been qualitatively successful in describing the experimental results, but the latter remain too sparse to permit more than limited quantitative comparison. This experimental situation limits detailed understanding of the optical potentials employed and permits little insight into other physical properties, such as the effect of resonance-width fluctuations, intermediate resonance structure, or even the spectroscopic characteristics of the nuclei excited by the inelastic scattering process.^{21,22} A good knowledge of inelastic neutron scattering is often important to the physical interpretation of scattering at low incident energies (1 to 2 MeV) for which the reaction cross section derived from the optical potential must be resolved into elastic and inelastic components before a meaningful comparison with either measured elastic or inelastic cross sections can be made.

This experimental study of neutron scattering from Mo, Sn, Sb, and Te was undertaken in an effort to provide a phenomenological understanding of neutron scattering in the mass region $A = 95$ to 130 necessary for a rigorous assay of optical potentials and excited nuclear structure at incident neutron energies of $\lesssim 1.5$ MeV. The effort was an extension of previous work.²³ Collectively, the results provide a detailed knowledge of neutron scattering from Mo, Ag, Cd, In, Sn, Sb, and Te. The results extend across the closed proton shell at $Z = 50$ and provide an experimental basis for a quantitative comparison with calculation.

2. EXPERIMENTAL METHOD

The pulsed-beam fast-neutron time-of-flight technique was employed throughout these experiments.²⁴ The apparatus consisted of a pulsed Van de Graaff accelerator, Mobley magnetic bunching system, and, in the later stages of the work, a multiangle detector system capable of making simultaneous time-of-flight measurements at 8 to 10 scattering angles.^{25,26} An on-line computer complex was employed in data acquisition, storage, on-line processing, and feedback control to the accelerator.²⁷ A detailed description of the apparatus and its use can be found in Refs. 26 and 27.

Neutrons were produced by means of the $\text{Li}^7(p,n)\text{Be}^7$ reaction. The metallic lithium targets were varied in thickness so as to provide an incident neutron resolution at the scattering samples of $\lesssim 20$ keV. The scattered neutron resolution was 1.0 to 2.5 nsec/m. This was sufficient to resolve the elastic scattered neutron group from most inelastic components and to clearly define a number of inelastically scattered neutron groups. Measurements were made at eight to ten neutron scattering angles ranging

from 20 to 150° and at incident neutron energy intervals of $\lesssim 25$ keV from 0.3 to 1.5 MeV. The scattering samples were right cylinders of the elemental metal and were struck by the incident neutrons on their lateral surfaces. A number of the measurements employed samples 17.8 mm in diameter and 17.8 mm high. Larger samples (20.3 mm in diameter and 20.3 mm high) were also used, particularly when a maximum sensitivity was desired. The sensitivity of the apparatus varied with the particular experimental configuration, but at best was $\lesssim 4$ mb/sr. The detectors were sensitive to neutrons of < 200 keV, but measurements at these low energies tended to be tedious and difficult to calibrate accurately. Therefore, the minimum neutron energy accepted for a cross-section determination was in the range from 200 to 300 keV.

All measured values were normalized relative to the known differential elastic scattering cross sections of carbon.² At scattered neutron energies $\gtrsim 1.2$ MeV a secondary standard, zirconium, was also used. Scattering from the "standard" samples (carbon and/or zirconium) was determined for every set of measurements, thereby providing a daily determination of the calibration. The cross sections of the "unknown" samples were deduced from the standard measurements, the known standard cross sections, and the observed elastic and inelastic scattering from the "unknown" samples by means of a special-purpose data-processing computer program.²⁶ This program derived the desired elastic and inelastic scattering cross sections relative to the standard cross sections from the measured time-of-flight distributions, the respective sample densities, and the incident flux. The results were corrected for: multiple scattering by use of a Monte Carlo procedure, incident-beam attenuation, and angular resolution. The fully corrected cross sections were available in tabular form expressed as Legendre expansion in laboratory angle.

3. EXPERIMENTAL RESULTS

3.1. Elastic Neutron Scattering

The measured differential elastic neutron scattering cross sections were expressed as Legendre expansions of the form

$$\frac{d\sigma(\theta)}{d\Omega} = \frac{\sigma(\text{el})}{4\pi} \left[1 + \sum_{i=1}^5 \omega_i P_i(\theta) \right], \quad (1)$$

where P_i are Legendre polynomials, ω_i are coefficients, and $\sigma(\text{el})$ is the elastic neutron scattering cross section. Both ω_i and $\sigma(\text{el})$ were determined from the least-squares fit of Eq. (1) to the measured values. All results were expressed in the laboratory coordinate system. The results in the form of Eq. (1) described the individual measured values in the

laboratory angular interval from 20 to 150°. The validity of the expansion of Eq. (1) is confined to the measured angular interval. The coefficients ω_i derived from the experiment are, of course, sensitive to the particular angular placement of the individual differential-cross-section measurements (usually at $\sim 15^\circ$ intervals). The form of Eq. (1) provided a compact and valid representation of the measured values and permitted a reasonable comparison of measurements made at slightly different incident neutron energies and/or laboratory scattering angles. The quality of the description of the experimental points given by Eq. (1) is illustrated in Fig. 1, where the solid curve in the upper portion of the figure represents the fit of Eq. (1) to the measured differential cross sections (open circles) for the elastic scattering of 0.775-MeV neutrons from Mo. The experimental scattered neutron resolution was sufficient to resolve the elastic component from essentially all inelastic neutron groups for scattering from Mo, Sn, and Te. One isotope of Sb (121, 57% abundant) has an excited state at 37 keV.²⁹ Neutrons resulting in the inelastic excitation of this low-lying level were resolved only at a very limited number of incident neutron energies and angles (see below); therefore, all "elastic" scattering from Sb reported here includes the inelastic neutron component due to the excitation of this 37-keV state.

Fig. 1

Measured Differential Cross Sections for the Scattering of 0.775-MeV Neutrons from Mo. The upper portion of the figure pertains to elastic processes and the lower to the inelastic excitation of the 0.2-MeV state. The solid line in the upper part of the figure represents the fit of Eq. (1) to the experimental data. The curve in the lower portion of the figure is only a qualitative indication of the isotropy of the measured differential inelastic cross sections.

112-6664

The experimentally determined differential elastic scattering cross sections of Mo, Sn, Sb, and Te are respectively shown in Figs. 2-5. The format is that of Eq. (1). The illustrated values were obtained by averaging the available measurements within a 50-keV increment. In some instances as many as six independent measurements were made at essentially the same incident neutron energy. These appear in the figures (and tables) as a single average value. The quantities shown in Figs. 2-5 are listed in Tables 1-A, B, C, and D. The indicated errors $\delta\omega_i$ represent the standard deviations derived from a least-squares fit of Eq. (1) to the experimental values. As such, they indicate the "goodness" of the fit and the reproducibility of the measurements over limited energy intervals, but they are not necessarily inclusive of all experimental uncertainties. The errors in

Fig. 2

Differential Elastic Neutron Scattering Cross Sections of Mo Expressed in the Form of Eq. (1). Solid lines represent the results of optical-model calculations as described in Sect. 4 of the text. The dotted line is the total neutron cross section reported in BNL-325.³

Fig. 3

Differential Elastic Neutron Scattering Cross Section of Sn in the Form of Eq. (1). The curves indicate results of calculations using various indicated choices of optical-potential parameters as described in Sect. 4 of the text.

112-6652

Fig. 4

Differential Elastic Neutron Scattering Cross Section of Sb in the Form of Eq. (1). Solid curves have the same interpretation as in Fig. 2.

112-6651

Fig. 5

Differential Elastic Neutron Scattering Cross Section of Te. Format and curves are as per Fig. 2.

TABLE 1-A. Differential Elastic Neutron Scattering Cross Sections of Mo
Expressed in Form of Eq. (1)

E_n , (MeV)	σ, b	w_1	δw_1	w_2	δw_2	w_3	δw_3	w_4	δw_4	w_5	δw_5
.325	8.720	.764	.042	.475	.058	.134	.078	.076	.086	.032	.099
.350	8.430	.834	.055	.455	.072	.097	.104	.055	.112	-.033	.143
.375	8.400	.770	.047	.514	.063	.090	.086	.082	.095	-.061	.114
.400	8.330	.848	.045	.506	.058	.059	.085	.031	.092	-.124	.121
.425	8.340	.861	.031	.572	.042	.118	.057	.044	.063	-.035	.079
.450	8.340	.983	.026	.554	.035	.156	.050	.004	.054	.007	.068
.475	8.350	.977	.030	.589	.043	.148	.055	.059	.060	.036	.062
.500	8.350	1.008	.028	.571	.039	.113	.054	.054	.057	.000	.064
.525	8.160	.970	.047	.637	.067	.110	.087	.103	.094	.015	.100
.550	8.200	1.016	.032	.624	.044	.153	.059	.085	.065	.057	.073
.575	7.880	1.003	.036	.668	.051	.179	.066	.118	.073	.079	.076
.600	7.950	1.040	.017	.640	.024	.152	.033	.068	.036	.038	.040
.625	7.750	1.011	.034	.660	.048	.133	.062	.073	.068	-.009	.073
.650	7.800	1.042	.024	.619	.034	.115	.046	.056	.050	-.004	.057
.681	7.390	1.013	.033	.681	.047	.145	.061	.085	.068	-.004	.071
.700	7.380	1.040	.025	.668	.035	.144	.047	.078	.052	.013	.058
.725	7.160	1.053	.032	.700	.044	.141	.060	.066	.065	-.017	.071
.731	7.120	1.089	.034	.685	.046	.120	.063	.057	.068	-.026	.075
.750	7.320	1.090	.027	.657	.037	.094	.053	.023	.056	-.056	.066
.768	7.230	1.096	.034	.669	.045	.084	.068	.011	.069	-.057	.078
.775	7.380	1.102	.037	.669	.050	.093	.073	.005	.075	-.055	.085
.800	7.320	1.126	.025	.654	.034	.060	.053	.014	.053	-.065	.065
.831	6.940	1.153	.025	.717	.032	.123	.053	.037	.052	-.027	.060
.850	6.960	1.194	.025	.723	.031	.153	.051	.070	.053	.038	.067
.858	6.930	1.207	.030	.734	.037	.177	.060	.096	.062	.075	.078
.862	7.050	1.235	.032	.719	.042	.188	.062	.098	.066	.106	.085
.908	6.570	1.279	.027	.818	.035	.268	.053	.142	.057	.091	.078
.950	6.120	1.285	.030	.881	.040	.254	.056	.110	.061	-.033	.073
.956	6.220	1.290	.031	.879	.043	.237	.058	.090	.063	-.040	.073
.975	5.910	1.297	.039	.903	.054	.261	.072	.111	.079	-.020	.088
1.000	6.020	1.339	.026	.922	.034	.279	.050	.098	.053	-.033	.068
1.006	5.890	1.359	.027	.961	.035	.308	.051	.103	.055	-.035	.069
1.025	6.050	1.353	.032	.985	.043	.346	.060	.145	.065	.028	.076
1.050	6.030	1.399	.037	1.023	.047	.371	.070	.154	.076	.037	.099
1.056	5.940	1.411	.043	1.038	.056	.395	.082	.175	.088	.066	.115
1.075	5.750	1.373	.040	1.023	.053	.363	.075	.169	.081	.059	.101
1.104	5.450	1.399	.030	1.087	.039	.419	.059	.165	.063	.038	.083
1.110	5.440	1.385	.026	1.078	.033	.413	.049	.152	.053	.043	.069
1.125	5.310	1.353	.022	1.096	.030	.406	.042	.176	.045	.016	.055
1.145	5.230	1.391	.020	1.157	.027	.445	.038	.159	.043	.038	.045
1.150	5.230	1.397	.020	1.163	.027	.453	.038	.168	.043	.056	.042
1.156	5.060	1.377	.020	1.166	.028	.426	.038	.148	.043	.024	.039
1.166	5.090	1.384	.021	1.178	.029	.431	.038	.158	.044	.049	.033
1.200	5.110	1.482	.022	1.254	.028	.502	.041	.154	.047	.083	.047
1.208	5.110	1.484	.022	1.263	.028	.516	.044	.171	.046	.111	.063
1.255	5.120	1.548	.016	1.299	.021	.563	.032	.182	.034	.094	.044
1.262	5.090	1.547	.013	1.299	.016	.562	.025	.166	.027	.077	.033
1.300	4.940	1.553	.021	1.319	.028	.552	.040	.191	.047	.055	.039
1.305	4.820	1.544	.023	1.337	.031	.560	.044	.188	.051	.051	.040
1.312	4.830	1.540	.025	1.330	.034	.526	.047	.187	.056	.017	.038
1.350	4.890	1.547	.031	1.393	.041	.568	.058	.208	.069	.034	.052
1.355	4.950	1.544	.030	1.403	.041	.575	.056	.227	.068	.035	.043
1.362	4.970	1.550	.028	1.407	.036	.594	.053	.240	.061	.044	.054
1.395	4.870	1.552	.027	1.418	.036	.625	.052	.199	.059	.072	.057
1.400	4.830	1.547	.030	1.407	.040	.612	.058	.193	.066	.043	.061
1.408	4.780	1.547	.029	1.388	.036	.618	.057	.179	.060	.057	.081
1.441	4.840	1.557	.025	1.440	.032	.680	.049	.230	.052	.113	.071
1.450	4.960	1.549	.027	1.448	.035	.665	.054	.211	.057	.102	.077

TABLE 1-B. Differential Elastic Neutron Scattering Cross Sections of Sn
Expressed in Form of Eq. (1)

E_n , (MeV)	a, 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	7.190	1.108	.051	.593	.070	.175	.095	.096	.102	.075	.120
.350	7.300	1.130	.063	.664	.082	.152	.118	.082	.127	-.052	.163
.375	6.760	1.108	.065	.643	.087	.080	.120	.035	.131	-.089	.153
.400	7.070	1.224	.056	.682	.073	.144	.105	.033	.114	-.024	.142
.425	6.680	1.195	.039	.714	.054	.154	.072	.091	.079	.051	.088
.450	7.180	1.241	.023	.747	.031	.147	.043	.108	.046	.024	.057
.481	6.800	1.260	.037	.732	.051	.145	.069	.082	.073	.073	.078
.500	7.010	1.303	.040	.724	.053	.132	.076	.042	.082	.035	.093
.525	6.890	1.309	.038	.780	.050	.188	.072	.050	.076	.039	.085
.531	6.920	1.288	.040	.789	.053	.194	.074	.062	.080	.035	.089
.550	7.190	1.317	.026	.811	.033	.210	.050	.073	.054	.037	.067
.568	7.040	1.309	.025	.839	.034	.228	.047	.075	.051	.064	.057
.575	7.110	1.272	.028	.818	.039	.189	.052	.062	.057	.052	.063
.600	7.130	1.306	.023	.820	.032	.170	.044	.066	.048	.041	.056
.625	6.900	1.262	.033	.835	.046	.142	.060	.059	.067	-.026	.070
.650	7.180	1.281	.022	.823	.031	.149	.041	.072	.046	.002	.051
.675	6.910	1.240	.026	.867	.037	.164	.048	.095	.053	-.002	.057
.700	7.020	1.285	.015	.880	.019	.188	.027	.095	.030	.041	.036
.725	6.860	1.270	.034	.925	.047	.191	.062	.112	.068	.016	.073
.750	7.200	1.317	.031	.916	.042	.184	.058	.093	.063	-.004	.071
.775	6.920	1.297	.035	.959	.049	.195	.064	.094	.070	.009	.075
.800	7.010	1.319	.015	.941	.020	.173	.028	.073	.029	.011	.035
.825	6.720	1.327	.013	.974	.019	.230	.025	.128	.027	.080	.029
.856	7.040	1.352	.013	.949	.018	.231	.026	.140	.028	.105	.037
.875	6.840	1.324	.020	1.005	.027	.258	.037	.171	.040	.108	.048
.900	6.830	1.329	.020	1.013	.026	.250	.038	.159	.040	.061	.051
.906	6.740	1.331	.023	1.021	.031	.256	.044	.166	.047	.061	.060
.925	6.600	1.304	.020	1.035	.021	.232	.039	.166	.041	.006	.048
.950	6.730	1.317	.017	1.012	.020	.206	.036	.138	.038	-.025	.043
.955	6.740	1.319	.016	1.014	.018	.194	.034	.131	.035	-.034	.038
.970	6.550	1.276	.032	1.034	.040	.173	.062	.134	.066	-.074	.069
.991	6.560	1.313	.035	1.072	.048	.192	.069	.119	.074	-.096	.084
.995	6.650	1.306	.040	1.093	.055	.206	.077	.143	.083	-.083	.093
1.006	6.550	1.318	.041	1.073	.054	.187	.076	.120	.083	-.116	.098
1.025	6.370	1.295	.052	1.148	.070	.223	.096	.138	.105	-.096	.119
1.050	6.550	1.362	.037	1.149	.049	.251	.071	.127	.076	-.048	.097
1.056	6.500	1.373	.036	1.160	.048	.272	.069	.142	.074	-.024	.093
1.075	6.310	1.334	.030	1.174	.040	.279	.056	.163	.061	-.008	.074
1.104	6.500	1.369	.018	1.184	.024	.287	.067	.161	.040	-.013	.054
1.110	6.430	1.370	.017	1.196	.023	.298	.070	.174	.038	-.012	.051
1.125	6.420	1.318	.013	1.212	.017	.290	.061	.190	.028	-.009	.036
1.145	6.410	1.324	.014	1.228	.018	.271	.058	.145	.031	-.006	.041
1.150	6.330	1.319	.014	1.243	.019	.278	.064	.141	.031	-.003	.041
1.156	6.230	1.307	.014	1.246	.019	.268	.028	.133	.030	-.005	.040
1.175	6.040	1.301	.024	1.272	.033	.338	.045	.170	.049	.063	.055
1.204	6.060	1.369	.024	1.275	.032	.363	.045	.149	.049	.053	.061
1.210	6.030	1.377	.023	1.278	.031	.381	.044	.156	.048	.063	.059
1.225	6.020	1.369	.045	1.307	.062	.429	.083	.217	.091	.084	.102
1.240	6.080	1.369	.038	1.324	.051	.386	.070	.191	.077	.041	.090
1.243	6.140	1.358	.042	1.363	.057	.388	.078	.214	.085	.073	.098
1.250	6.170	1.349	.054	1.366	.074	.413	.100	.236	.110	.110	.125
1.275	5.880	1.297	.053	1.371	.074	.408	.097	.247	.110	.069	.113
1.300	5.880	1.340	.026	1.389	.034	.366	.050	.178	.057	.020	.066
1.325	5.710	1.345	.035	1.384	.048	.401	.066	.218	.075	.039	.080
1.356	5.890	1.406	.038	1.451	.050	.378	.071	.159	.080	-.029	.078
1.380	5.880	1.396	.034	1.448	.047	.381	.064	.193	.073	-.030	.068
1.400	5.950	1.439	.035	1.441	.046	.386	.067	.155	.074	.001	.080
1.405	5.920	1.440	.036	1.431	.048	.382	.071	.159	.076	.002	.096
1.420	5.790	1.435	.032	1.432	.044	.423	.062	.206	.067	.042	.081
1.425	5.780	1.441	.036	1.416	.049	.455	.069	.224	.075	.093	.091
1.443	5.880	1.462	.031	1.479	.041	.492	.060	.215	.065	.098	.084
1.450	5.820	1.438	.028	1.499	.037	.493	.053	.243	.057	.077	.072

TABLE 1-C. Differential Elastic Neutron Scattering Cross Sections of Sb
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	6.670	1.143	.050	.625	.070	.113	.094	.143	.103	.006	.113
.350	6.850	1.155	.067	.588	.089	.062	.128	.087	.138	-.149	.174
.362	6.740	1.064	.083	.592	.110	-.007	.156	.057	.169	-.319	.208
.400	6.950	1.234	.069	.573	.087	.018	.133	-.016	.143	-.238	.195
.450	6.940	1.317	.036	.661	.046	.079	.070	.026	.075	-.047	.103
.500	7.150	1.324	.029	.680	.038	.100	.058	.054	.062	.010	.085
.550	7.150	1.288	.032	.720	.042	.138	.053	.060	.051	.070	.051
.575	7.080	1.307	.030	.767	.041	.169	.051	.056	.047	.089	.043
.600	7.140	1.378	.009	.805	.012	.186	.019	.061	.019	.053	.023
.631	6.990	1.361	.020	.835	.027	.118	.043	.050	.042	-.043	.049
.641	6.960	1.356	.020	.828	.026	.082	.043	.050	.042	-.075	.049
.666	6.900	1.367	.036	.844	.047	.109	.077	.040	.072	-.053	.085
.675	6.890	1.378	.040	.843	.052	.139	.085	.039	.079	-.016	.093
.725	6.820	1.361	.064	.867	.086	.198	.122	.107	.127	.073	.147
.750	6.870	1.360	.049	.896	.067	.167	.091	.103	.099	.017	.115
.775	6.510	1.326	.046	.897	.065	.134	.086	.079	.097	-.018	.101
.800	6.560	1.376	.020	.927	.028	.150	.040	.040	.046	-.034	.052
.825	6.300	1.337	.034	.919	.048	.157	.065	.063	.074	-.024	.079
.850	6.720	1.393	.036	.951	.048	.217	.068	.103	.073	.076	.089
.875	6.500	1.358	.035	.993	.047	.230	.065	.131	.070	.097	.083
.906	6.670	1.437	.029	1.068	.037	.376	.056	.183	.059	.135	.079
.925	6.570	1.431	.021	1.110	.027	.368	.041	.195	.043	.058	.055
.950	6.670	1.472	.024	1.086	.031	.338	.048	.138	.051	.001	.068
.956	6.650	1.472	.021	1.091	.027	.282	.042	.114	.044	-.034	.039
.975	6.670	1.447	.035	1.105	.045	.232	.035	.122	.036	-.081	.047
1.000	6.700	1.472	.035	1.158	.045	.283	.041	.118	.044	-.074	.059
1.006	6.640	1.487	.036	1.194	.046	.310	.036	.130	.039	-.078	.052
1.016	6.810	1.474	.042	1.236	.054	.325	.036	.183	.038	-.056	.051
1.050	6.630	1.534	.032	1.289	.041	.413	.064	.179	.068	.012	.093
1.058	6.600	1.565	.033	1.297	.042	.433	.065	.184	.069	.029	.095
1.100	6.120	1.501	.040	1.307	.041	.409	.059	.208	.081	.019	.105
1.106	6.020	1.505	.038	1.315	.037	.424	.050	.233	.077	.021	.097
1.116	5.920	1.466	.039	1.299	.034	.388	.044	.219	.078	.001	.096
1.150	5.900	1.480	.027	1.363	.021	.419	.030	.175	.058	-.022	.059
1.158	5.720	1.479	.029	1.367	.020	.416	.027	.125	.063	-.027	.060
1.200	5.570	1.522	.037	1.416	.053	.504	.064	.209	.081	.006	.032
1.206	5.510	1.524	.040	1.407	.058	.506	.069	.209	.087	.008	.041
1.216	5.530	1.553	.049	1.434	.071	.559	.083	.262	.106	.010	.040
1.255	5.680	1.549	.032	1.494	.044	.517	.059	.237	.073	-.009	.037
1.262	5.700	1.557	.028	1.497	.038	.516	.053	.240	.063	-.011	.046
1.290	5.450	1.517	.030	1.514	.041	.489	.056	.213	.068	-.021	.055
1.293	5.410	1.517	.034	1.506	.046	.480	.065	.215	.077	-.026	.069
1.300	5.200	1.490	.030	1.543	.042	.505	.055	.227	.070	-.011	.046
1.325	5.070	1.464	.035	1.532	.049	.488	.065	.274	.082	.007	.054
1.356	5.500	1.520	.032	1.578	.046	.546	.059	.237	.075	.001	.031
1.375	5.390	1.500	.037	1.651	.054	.558	.067	.307	.080	-.012	.054
1.400	5.620	1.557	.034	1.654	.047	.597	.061	.265	.071	.015	.058
1.406	5.550	1.561	.030	1.661	.040	.598	.055	.292	.059	.019	.072
1.425	5.230	1.558	.038	1.647	.054	.612	.070	.315	.077	.048	.087
1.443	5.500	1.590	.031	1.624	.042	.627	.060	.241	.065	.045	.079
1.450	5.430	1.574	.039	1.639	.053	.633	.074	.266	.081	.061	.098

TABLE 1-D. Differential Elastic Neutron Scattering Cross Sections of Te
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	6.050	1.288	.022	.691	.027	.062	.044	.036	.047	-.098	.060
.375	6.270	1.231	.031	.719	.039	-.060	.063	-.016	.067	-.138	.088
.400	6.410	1.241	.023	.708	.029	-.081	.046	-.068	.049	-.113	.065
.425	6.419	1.329	.025	.667	.032	-.010	.051	-.076	.055	-.034	.072
.450	6.830	1.307	.031	.723	.039	.015	.061	.016	.065	-.049	.087
.480	7.090	1.304	.038	.743	.050	.106	.074	.049	.080	.030	.099
.504	7.050	1.292	.038	.746	.050	.093	.073	.030	.079	.037	.097
.511	7.020	1.279	.034	.727	.045	.079	.064	.014	.070	.043	.083
.530	6.960	1.286	.031	.763	.041	.043	.061	.028	.066	-.024	.081
.545	6.940	1.293	.032	.809	.042	.038	.062	.063	.067	-.036	.084
.550	6.920	1.292	.030	.816	.041	.031	.058	.071	.063	-.045	.077
.568	6.980	1.297	.031	.841	.042	.022	.063	.078	.067	-.079	.085
.575	7.000	1.337	.034	.834	.044	.054	.070	.075	.074	-.055	.098
.600	7.030	1.356	.023	.881	.029	.083	.046	.104	.049	-.019	.066
.625	6.960	1.336	.022	.857	.028	.052	.045	.059	.048	-.057	.063
.650	6.660	1.321	.032	.899	.042	.113	.062	.090	.066	-.025	.083
.669	6.620	1.321	.032	.900	.043	.094	.063	.067	.068	-.024	.084
.675	6.540	1.326	.034	.923	.045	.124	.065	.080	.070	-.016	.085
.687	6.790	1.359	.030	.907	.037	.101	.059	.040	.062	-.037	.083
.732	6.710	1.351	.041	1.015	.055	.097	.078	.068	.085	-.054	.098
.757	6.920	1.336	.049	1.025	.065	.098	.093	.095	.102	-.048	.121
.775	7.110	1.379	.056	1.017	.041	.113	.066	.083	.070	-.032	.092
.787	7.140	1.365	.064	1.018	.035	.113	.055	.091	.059	-.032	.078
.825	6.680	1.399	.074	1.060	.049	.089	.079	.092	.084	-.117	.109
.881	6.420	1.409	.032	1.174	.040	.204	.064	.138	.066	-.043	.086
.900	6.430	1.407	.019	1.227	.024	.284	.039	.186	.039	.022	.051
.925	6.270	1.443	.022	1.269	.028	.328	.043	.198	.044	.035	.055
.931	6.340	1.441	.021	1.253	.027	.325	.041	.200	.045	.044	.055
.950	6.270	1.449	.016	1.251	.021	.337	.031	.213	.033	.058	.041
.968	6.140	1.468	.018	1.273	.023	.312	.034	.169	.037	.027	.045
.975	6.080	1.465	.020	1.288	.026	.339	.038	.177	.041	.054	.049
1.000	6.040	1.408	.023	1.226	.028	.201	.045	.072	.047	-.051	.064
1.025	6.080	1.439	.020	1.315	.025	.265	.040	.099	.042	-.035	.056
1.050	6.160	1.443	.038	1.341	.048	.290	.075	.153	.079	-.029	.107
1.075	6.500	1.508	.032	1.408	.041	.395	.064	.241	.068	.029	.091
1.100	6.500	1.483	.044	1.430	.055	.395	.087	.256	.092	.060	.125
1.125	6.560	1.522	.037	1.390	.047	.361	.075	.219	.080	-.007	.106
1.156	6.260	1.471	.044	1.436	.056	.311	.088	.219	.094	-.002	.126
1.166	6.190	1.471	.043	1.428	.055	.266	.087	.195	.092	-.060	.123
1.200	5.860	1.447	.030	1.545	.038	.324	.059	.214	.062	-.012	.085
1.208	5.900	1.457	.032	1.540	.041	.349	.064	.220	.067	.001	.092
1.250	5.590	1.478	.025	1.540	.032	.330	.049	.128	.052	-.081	.065
1.258	5.470	1.471	.030	1.520	.039	.316	.059	.091	.064	-.107	.078
1.300	5.200	1.468	.040	1.563	.056	.305	.073	.047	.093	-.059	.037
1.308	5.160	1.486	.051	1.586	.071	.298	.093	.055	.117	-.079	.050
1.350	5.300	1.455	.039	1.759	.056	.436	.071	.254	.093	-.011	.020
1.356	5.360	1.451	.044	1.787	.062	.447	.078	.314	.102	-.014	.025
1.375	5.540	1.482	.041	1.820	.057	.539	.074	.420	.095	-.014	.025
1.400	5.500	1.533	.041	1.772	.053	.590	.077	.345	.089	.057	.078
1.406	5.360	1.547	.049	1.765	.065	.627	.093	.329	.107	.087	.093
1.416	5.310	1.596	.056	1.745	.074	.675	.105	.357	.123	.115	.096
1.441	5.360	1.584	.041	1.759	.052	.699	.081	.311	.086	.175	.117
1.450	5.510	1.623	.054	1.771	.067	.741	.105	.323	.111	.243	.152

the measured total elastic scattering cross sections were difficult to assay as a number of uncertain experimental factors entered into such errors. It was subjectively estimated that the probable errors in the measured total elastic scattering cross sections were $\sim 8\%$, including the effect of uncertainties in the reference cross section, that of carbon. The reproducibility of the measured total elastic cross sections was good despite the fact that some of the results were obtained four years apart and with different experimental arrangements. All of the values given in Figs. 2-5 and Tables 1-A, B, C, and D have been corrected for multiple scattering, beam attenuation, and angular resolution as outlined in Sect. 2.

3.2. Inelastic Neutron Scattering

The differential inelastic excitation cross sections of states in Mo at 0.20 ± 0.01 , 0.50 ± 0.04 , and 0.79 ± 0.06 MeV were determined. In addition the inelastic neutron excitation of a complex of states near 1.05 MeV was observed. All of the observed Mo differential inelastic cross sections were judged to be isotropic within the measured precisions of ≈ 3 mb/sr. An example of this isotropy is indicated in the lower part of Fig. 1, which shows the observed differential cross section for the excitation of the 0.2-MeV state in Mo by 0.775-MeV incident neutrons. The cross sections for the excitation of the 0.5-MeV state were not well-determined either as to reaction Q value or magnitude of cross section. This was due to the presence of elastically scattered neutrons originating from the second neutron group from the source reaction $\text{Li}^7(p,n)\text{Be}^{7*}$, which had very nearly the same scattered neutron energy as the inelastic neutrons. The known yield of the second source group and the measured elastic scattering cross sections were used to correct the observed inelastic results for elastic contamination due to the second neutron group. The scattered-neutron spectrum corresponding to the excitation of the 0.79-MeV "state" consisted of at least three components with separations of ≈ 50 keV. These components were not resolved at all incident energies; thus this composite of levels was grouped into a single "state" with a relatively large uncertainty in the Q value. The excitation of states near 1.05 MeV was too uncertain in magnitude to provide a quantitative cross section other than a limiting value ≈ 4 mb/sr. The experimentally measured inelastic cross sections of Mo are summarized in Fig. 6 and listed in Table 2. The uncertainties quoted for both cross sections and Q values are best judgments of the respective uncertainties and include the probable errors associated with the carbon cross sections used for normalization. The inelastic excitation cross sections of Mo given in Fig. 6 and Table 2 were derived from differential measurements made at 6 to 10 scattering angles between 30 and 150°. All inelastic cross sections of Mo (as well as of Sn, Sb, and Te) were corrected for multiple scattering and the effect of the incident-beam attenuation in the manner outlined in Sect. 2.

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Fig. 6. The Observed Inelastic Excitation Cross Sections of Mo. The crosses indicate the results of the present experiment, the open circles are from Ref. 9. Solid and dashed curves are the result of calculations described in Sect. 4 of the text.

tering from Sb corresponding to the excitation of states at 0.16 ± 0.01 and 0.54 ± 0.04 MeV. The respective observed inelastic excitation cross sections are shown in Fig. 7 and listed in Table 3. A state near 1.05 MeV was also qualitatively observed; however, the excitation was not intense enough to permit a definitive measurement of cross sections. A careful search was made for the neutron group corresponding to the excitation of a reported state in Sb^{121} (57%) at ~ 37 keV.^{28,29} Under the most favorable experimental conditions it was possible to resolve this neutron group experimentally as shown in Fig. 8. The figure shows three curves: a) the measured time distribution for scattering of 560-keV neutrons from Sb at 135° ; b) a similar spectrum obtained by scattering from natural uranium; c) a "control" spectrum obtained by scattering from Sn. The inelastic excitation of the known 44-keV (2^+) state of U^{238} is clearly evident and serves as a standard for calibrating the time scale.³¹ By use of this calibration, a value of $Q = -0.037 \pm 0.003$ MeV was measured for the first inelastic reaction in Sb. The respective cross section was determined to be 300 ± 60 mb.

At incident neutron energies near 1.5 MeV a diffuse inelastic neutron group corresponding to a "level" in Sn at ~ 1.2 MeV was observed. The wide distribution in energy of this group indicated contributions from a number of states the excitation of any one of which was $\lesssim 4$ mb/sr. Due to this complexity and the relatively narrow incident energy interval available (1.4 to 1.5 MeV), this complex of states near 1.2 MeV was not examined in detail. As discussed in Sect. 4, elemental Sn has two odd-A isotopes with a total abundance of $\sim 15\%$. These nuclei are reported to have a complex excited structure that could result in a number of inelastically scattered neutron groups.²⁸ Careful examination of the Sn measurements indicated a "background" that could be due to the inelastic excitation of a number of states in these low-abundant odd-A isotopes. However, the intensity was too small to permit a quantitative determination of either cross section or reaction Q value.

Two prominent inelastic neutron groups were observed in scat-

TABLE 2. Inelastic Excitation Cross Sections of Mo

Q = -0.20 ± 0.01 MeV			Q = -0.50 ± 0.04 MeV		
E_n , (MeV) ^a	σ , b	$\delta\sigma$, b	E_n , (MeV) ^a	σ , b	$\delta\sigma$, b
.475	.300	.090	.850	.530	.200
.500	.250	.080	.925	.200	.080
.525	.320	.100	.975	.200	.080
.575	.300	.070	1.025	.180	.080
.600	.150	.070	1.075	.120	.060
.625	.270	.050	1.125	.140	.050
.650	.250	.050	1.175	.120	.040
.675	.200	.040	1.225	.120	.040
.700	.190	.030	1.275	.070	.040
.725	.180	.030	1.325	.070	.040
.750	.140	.030	1.425	.130	.050
.775	.160	.040	1.475	.080	.030
.800	.120	.030	1.500	.150	.060
.825	.130	.030			
.850	.120	.030			
.875	.160	.040			
.925	.130	.030			
.950	.170	.040			
.975	.150	.040			
1.025	.120	.030			
1.075	.110	.020			
1.125	.100	.020			
1.175	.120	.030			
1.225	.110	.030			
1.275	.090	.020			
1.325	.100	.020			
			Q = -0.79 ± 0.06 MeV ^(b)		
			E_n , (MeV) ^a	σ , b	$\delta\sigma$, b
			1.100	.550	.090
			1.125	.710	.100
			1.175	.820	.100
			1.175	.770	.100
			1.225	.760	.110
			1.275	.760	.110
			1.325	.800	.120
			1.375	.600	.100
			1.425	.680	.090
			1.450	.760	.100
			1.475	.760	.150
			1.500	.570	.150

^a Incident energy uncertainty is ± 10 keV.

^b See Section 3 of text for explanation of Q value.

TABLE 3. Inelastic Excitation Cross Sections of Sb

Q = -0.16 $\pm$ 0.01 MeV			Q = -0.54 $\pm$ 0.04 MeV		
E_n , (MeV) ^a	σ , b	$\delta\sigma$, b	E_n , (MeV) ^a	σ , b	$\delta\sigma$, b
.500	.230	.050	.925	.170	.090
.550	.137	.050	.975	.240	.090
.600	.165	.040	1.075	.180	.080
.625	.185	.030	1.125	.210	.050
.650	.164	.030	1.175	.250	.090
.700	.185	.040	1.225	.190	.050
.725	.257	.050	1.275	.230	.040
.750	.242	.040	1.325	.200	.040
.775	.222	.050	1.425	.270	.050
.825	.240	.050	1.500	.240	.070
.850	.170	.040			
.875	.216	.050			
.925	.240	.040			
.975	.260	.060			
1.025	.220	.040			
1.075	.220	.040			
1.100	.185	.050			
1.125	.220	.040			
1.150	.240	.050			
1.175	.190	.040			
1.225	.201	.030			
1.275	.206	.040			
1.325	.247	.050			

^a Incident energy uncertainty is $\pm$ 10 keV

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Fig. 7. The Measured Inelastic Neutron Excitation Cross Sections of Sb. Circular points represent the results of the present work; the crosses are taken from Ref. 9. The solid curves indicate theoretical calculations as described in Sect. 4 of the text.

instance were the observed differential inelastic cross sections of Te significantly anisotropic.

Three states in Te were excited by inelastic neutron scattering corresponding to reaction Q values of -0.65 ± 0.02 , -0.75 ± 0.02 , and -0.85 ± 0.02 MeV. The respective excitation cross sections were in the approximate ratios 1.0:2.0:2.4, or about that of the abundance of the contributing even isotopes of Te. In order to obtain "good" quantitative cross-section values the contributions were combined to give the inelastic neutron cross sections corresponding to an average "state" at 0.75 MeV. The experimentally determined inelastic excitation cross sections are shown in Fig. 9 and listed in Table 4. The indicated uncertainties have the same sense as discussed above for Mo. In no

Fig. 8

Time Spectra Obtained by Scattering 560-keV Neutrons from Sb (top), U(nat) (center), and Sn (bottom). Scattering angle was 135° and flight path 3.4 m. The neutron group corresponding to the excitation of a 37-keV state of Sb is evident in the upper portion of this figure. The energy scale is determined from the observed excitation of the known 44-keV state in U^{238} . Sn serves as a control. The backgrounds have not been subtracted from these experimental distributions, and the vertical bars denote the relative standard deviations of the respective points.

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Fig. 9. Observed Inelastic Scattering Cross Sections of Te (solid data points) Are Shown at the Left. The results of calculations are indicated by curves (see Sect. 4). The right portion of the figure schematically outlines the respective nuclear structure.²⁸

4. DISCUSSION AND INTERPRETATION

4.1. Experimental

At the energies and for the elements studied in these experiments, the total neutron cross section consists almost entirely of elastic and inelastic scattering; thus it is gratifying to note that the measured Mo, Sn, and Sb scattering results are in agreement with the total neutron cross sections reported in BNL-325³ and also with the results of more recent measurements of total cross section.³² This is illustrated in Fig. 2. The differences between the total and elastic neutron cross sections of Mo are essentially equivalent to the total inelastic cross sections deduced from the data of Fig. 6. The observed elastic scattering cross sections of Te tend to be several hundred mb larger than the previously reported total cross sections and the total scattering cross sections of Langsdorf *et al.*^{2,3} However, the elastic scattering cross sections displayed an energy-dependent structure that made it difficult to compare the values observed in these experiments with those measured with different (and usually broader) energy resolution. The total scattering measurements of Langsdorf *et al.* do tend to show a similar structure despite the fact that they were made with an incident neutron resolution 4-6 times broader than that of the present work.

The previously reported measurements of elastic neutron scattering from Mo, Sn, Sb, and Te near incident neutron energies of 1.0 MeV (Refs. 4-8) are compared with those of the present work in Fig. 10. In the case of Sn and Te, the agreement between the various results and those of the present work is remarkably good. In the case of Mo, small discrepancies between the measurements exist at back angles. These may well be due to the

TABLE 4. Inelastic Excitation Cross Sections of Te

E_n , (MeV) ^a	Q , (MeV) ^b	σ ,b	$\delta\sigma$,b
1.125	-0.75	0.412	0.060
1.175	$\begin{Bmatrix} -0.65 \\ -0.75 \\ -0.85 \end{Bmatrix} = \sim -0.75$	$\begin{Bmatrix} 0.148 \\ 0.199 \\ 0.244 \end{Bmatrix} = -0.591$	0.050
1.225	-0.75	0.463	0.050
1.225	-0.75	0.602	0.060
1.275	-0.75	0.466	0.050
1.275	-0.75	0.588	0.060
1.325	-0.75	0.370	0.080
1.375	-0.75	0.426	0.080
1.425	-0.75	0.585	0.060
1.425	-0.75	0.515	0.070
1.475	-0.75	0.581	0.070
1.500	-0.75	0.612	0.080
1.500	-0.75	0.663	0.080

^a Incident energy uncertainty is ± 10 keV

^b Composite Q value accept where otherwise noted (see text)

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Fig. 10

Differential Elastic Scattering Angular Distributions as Determined at an Incident Neutron Energy of ~ 1.0 MeV. The results of the present work are indicated by solid squares. The other data symbols refer to results as follows: $\circ$ = Ref. 4; $\triangle$ = Ref. 7; $\blacksquare$ = Ref. 33; and $\square$ = Ref. 8. The solid curves are "eye guide" indications of the angular dependence of the present work; the dashed lines represent the results of optical-model calculations as described in Sect. 4 of the text.

cross sections for the 0.2- and 0.79-MeV states do not correspond to those of this work in either magnitude or shape. Inelastic gamma-ray measurements

inclusion of a small amount of inelastic neutron scattering in the previously measured elastic scattering. The results for Sb at back angles disagree with those of the present work by amounts that exceed effects due to inelastic scattering. This discrepancy is difficult to explain, particularly as the results of the present work for all the elements of these experiments were obtained at essentially the same time and would be subject to many of the same systematic errors, and yet only results for Sb appear to differ appreciably from previously reported values at ~ 1.0 MeV.

The observed elastic neutron scattering cross sections of Mo and Sn (see Figs. 2 and 3, respectively) are reasonably smooth functions of the incident neutron energy. That of Sb (see Fig. 4) shows some possible periodicity with energy. The elastic scattering cross section of Te (see Fig. 5) clearly displays an energy-dependent structure with a period of several hundred keV. This effect in Te verifies the recent results of Cox in the energy range from 0.7 to 1.2 MeV.³⁴ He specifically reports a maximum in the elastic cross section of Te, very similar to that shown in Fig. 5 at an incident energy of 0.8 MeV, and attributes this and similar structure to the effect of "intermediate resonances."²²

Glazkov *et al.* have reported the inelastic neutron excitation cross sections for a number of states in Mo.⁹ Their results pertaining to the 0.5-MeV state (shown in Fig. 6) are similar to those of the present experiments; however, their excitation

by Kikuchi *et al.* do lead to an inelastic excitation cross section for the 0.79-MeV state in good agreement with that obtained here.¹² In addition, the same gamma-ray measurements indicate a ~5-mb/sr cross section for the excitation of a state at ~1.05 MeV in accord with qualitative results of present experiment.

The inelastic excitation cross sections of the 0.16- and 0.54-MeV states in Sb obtained in this experiment are similar to those reported by Glazkov⁹ (see Fig. 7). The observed "state" at 0.54 MeV is probably the composite of the two states ($1/2^+$ and $3/2^+$) which were not resolved due to the confusion with the elastic scattering component from the second source group described above. Elemental Sn is composed of a number of isotopes but only two (of mass numbers 117 and 119) are reported to have states with excitation energies of ≈ 1.1 MeV²⁸ and their total abundance is ~16%. Careful experimental measurements revealed only a small "background" corresponding to inelastic excitation of states at ≈ 1.1 MeV as described above. In no case could a specific neutron group be reliably identified. The broad neutron group corresponding to the excitation of a state at ~1.2 MeV qualitatively consisted of three or more components, none of which correspond to differential excitation cross sections of more than 4 mb/sr. This magnitude is somewhat smaller than indicated by inelastic gamma-ray experiments.¹²

4.2. Theoretical Calculations

Theoretical calculations were carried out based upon the optical model and the statistical theory of Hauser-Feshbach or Wolfenstein.^{13,17-20} The surface-absorption optical potential of Moldauer¹⁹ was employed, defined as follows:¹⁹

$$\begin{aligned}
 & -Vq(r) - iWP(r) + V_{s0} \left(\frac{\hbar}{\mu \pi c} \right) \frac{\sigma}{2} \cdot \frac{\ell}{r} \frac{d}{dr} [q(r)]; \\
 & q(r) = \left[1 + \exp \left(\frac{r-R}{a} \right) \right]^{-1}; \\
 & p(r) = \exp \left[- \left(\frac{r-R-c}{b} \right)^2 \right]; \\
 & R = r_0 A^{1/3} + r_1.
 \end{aligned} \tag{2}$$

The parameters a , b , c , V_{s0} , r_0 , and r_1 were kept fixed at the following values:

$$\begin{aligned}
 r_0 &= 1.13 \text{ fm}; & r_1 &= 0.6 \text{ fm}; \\
 a &= 0.62 \text{ fm}; & b &= 0.5 \text{ fm}; \\
 c &= 0.5 \text{ fm}; & V_{s0} &= 7 \text{ MeV}.
 \end{aligned} \tag{3}$$

The real (V) and imaginary (W) potential values were varied in the interval 40-50 MeV and 2-14 MeV, respectively. The statistical theory was employed to deduce compound elastic and inelastic cross sections from the reaction cross section.

The element Mo consists of a number of isotopes with different excited structures. This complexity made it difficult to compare the reported structure with the observed inelastic neutron scattering and would have led to very extensive computations if each of the isotopes were treated individually. For these reasons, the comparison with experiment and the computations were based upon the simplified "model" element shown in Fig. 11. This "model" element is a reasonable representation of the actual structure. The isotopic constituency of Te and Sb is relatively simple and can be directly associated with the experimental results (see Figs. 9 and 12) and used in the calculation.

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Fig. 11. Level Structure of Mo. To the left are the reported isotopes, abundances, and excited states;²⁸ at the center are the experimentally observed structures, and to the right the "model" used as a basis for interpreting experiment and carrying out calculations.

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Fig. 12. Reported Level Structures of Sb Compared with the Experimental Results²⁸

The V and W portions of the optical potential were adjusted to obtain the best agreement with the measured differential elastic scattering cross sections of Mo, Sn, Sb, and Te. The adjustments were made by calculating a mesh of V and W values extending from 40 to 50 MeV in increments of 0.5 MeV and from 2 to 14 MeV in increments of 3 MeV, respectively. The results obtained at the mesh points were subjectively compared with experiment at ~ 100 -keV incident-energy intervals. In a few cases, a limited section of the V - W mesh was selected as a region of good agreement with experiment, and a further adjustment of V and W carried out to obtain a minimum χ^2 value.

Such adjustment procedures were only carried out at a few isolated energies and led to results that were felt to be little, if any, improvement over the subjective selection of V and W values from the initial mesh calculations. The latter procedure has the further merit of achieving a rapid comparison with a large number of experimental distributions over a wide range of incident neutron energy as contrasted to the tedious, if not economically unfeasible, adjustments to fit each of the measured distributions. The intermediate method of subjectively smoothing the energy dependence of the measurements and then applying a fitting procedure was not employed, as it was believed to have no advantage over a straightforward judgment derived from the results of the mesh calculations. Following the above reasoning, it was decided to subjectively select the "best" V and W potential values directly from a comparison of the mesh calculations and experimental values. Representative results obtained by this comparison method are given in Figs. 2 through 5, where the respective V and W potential values and the corresponding calculated cross sections are compared with experiment.

The most experimentally unambiguous elastic scattering was from Sn, since inelastic processes are not a factor below an incident neutron energy of ~ 1.2 MeV. The "best" optical potential values were found to be $V = 45.5$ MeV and $W = 8$ MeV, and are indicated by the solid curve of Fig. 3. Other, and less satisfactory, values of V are also indicated. The experimental ω_i are well described by the calculations using these "best" value (solid curves); variations from the value $W = 8$ MeV led to calculated ω_i disagreeing with experiment. It should again be noted that the experimental values of ω_i are obtained from results measured in the angular interval from 20 to 150° and do describe the measured quantities only within this interval. The calculated values are determined from the potential and may therefore differ slightly from the experimental quantities, which were measured over a limited angular interval and were influenced by the particular selection of observational scattering angles. Despite this distinction the calculated values of $\sigma(\text{el})$ and ω_i compare favorably with experimentally deduced values. This agreement is further evident in the comparison of measured and calculated angular distributions shown in Fig. 10.

A comparison between calculated and experimental differential elastic scattering cross sections of Sb is shown in Fig. 4 and for Te in Fig. 5. In both of these cases inelastic scattering must be considered in the calculations throughout much of the measured incident-neutron-energy interval. The "best" potential values for Sb were judged to be $V = 45.0$ MeV and $W = 8$ MeV, and for Te these were $V = 44.5$ MeV and $W = 8.0$ MeV. The calculated Te values must be compared with a 200-300-keV average of the measurements if the basis of the statistical model employed is to be reasonably valid in the apparent presence of an intermediate structure. Calculation was less descriptive of experiment in the case of Mo (see Fig. 2). The total elastic cross section and the ω_i coefficient are reasonably well described by the values $V = 46$ MeV and $W = 8$ MeV. The

experimental agreement with the calculated ω_2 coefficient is less satisfactory. However, comparison of calculation and experiment in the format of Eq. (1) is particularly sensitive. Indeed, when compared as individual angular distributions, calculation and experiment yield very similar elastic distributions even in the case of Mo, as shown in Fig. 10.

The results of these experiments and other recent work by this group provide a good phenomenological basis for the assay of details of the optical potential in the vicinity of the closed proton shell at $Z = 50$.²³ Comparable experimental elastic and inelastic neutron scattering cross sections are available for the elements $Z = 47$ to 52. All of these experimental measurements have been compared with the results of calculations based upon the surface-absorption optical potential of Eq. (2), keeping all potential parameters other than V and W constant. The latter were adjusted, as described above, to give the "best" description of the experimental data. The resulting real and imaginary potential values are summarized in Table 5. The V and W values were judged to be defined by experiment to within 0.5 and 3.0 MeV, respectively; thus, the variations in V and W given in Table 5 are significant. Since the measurements were all made by the same group using the same equipment and often at the same time, the likelihood of a systematic experimental variation from element to element was appreciably reduced. Variations in either V or W alone did not give a satisfactory description of the measured values. Both had to be adjusted. It thus appears that the proton shell closure at $Z = 50$ (Sn) marks a transition point in both the real and imaginary portions of the optical potential. Similar changes in W values have been noted near the doubly closed shell at $A = 208$.³⁵ Further, the effect near $Z = 50$ noted in these experiments can be construed from previous work, although reported calculations and measurements were made principally near an incident energy of ~ 1.0 MeV and with insufficient mass definition to well define the area near $Z = 50$.¹⁴ The incident neutron energy of ~ 1.0 MeV is, moreover, often not particularly sensitive to changes of V and W in this mass region, and it is necessary to carry the comparison of calculation and measurement to appreciably different energies to achieve a reasonable sensitivity in the adjustment of

TABLE 5. Comparison of Real (V) and Imaginary (W) Parts of the Optical Potential for Elements near $Z = 50$

Element	Z	Average A	V (MeV)	W (MeV)
Ag	47	108	46.0	16.0
Cd	48	112	46.0	16.0
In	49	115	46.0	16.0
Sn	50	119	45.5	8.0
Sb	51	122	45.0	8.0
Te	52	128	44.5	8.0

these two parameters.¹⁵ Such energy intervals were available in the present work and have led to the results summarized in Table 5. The above conclusions were, of course, based upon an optical potential of the form of Eq. (2), where only V and W were varied to achieve a description of the experimental result. The agreement with experiment so obtained does not imply a uniqueness nor is a variation in the other parameter(s) of Eq. (2) or a change in the potential form excluded. The above choice of potentials gives, at best, a qualitative description of the reported scattered neutron polarization¹ and does not have an energy dependence necessary for application over an extended incident neutron energy interval.²⁰ However, the use of these potentials does result in a good phenomenological description of differential elastic neutron scattering in the mass-energy region of these experiments.

The odd-A isotopes of Sn (117, 8.6% and 119, 8.6%) have $1/2^+$ ground states and first two excited states of $3/2^+$ and $11/2^+$ in that order.²⁸ Inelastic excitation of the $11/2^+$ state should be very small at the incident neutron energies of the present experiment. A $3/2^+$ state in Sn¹¹⁹ is reported at an excitation energy of 25 keV and was not resolved from the elastically scattered neutron group in these experiments. By means of the optical potentials described above and Hauser-Feshbach theory, the excitation of the $3/2^+$ (160-keV) state in Sn¹¹⁷ was calculated to be ≈ 4 mb/sr when corrected for isotopic constituency. This small value of the cross section accounts for only the qualitative observation of a positive "background" due to the excitation of such a state. Both Sn¹¹⁷ and Sn¹¹⁹ are reported to have excited states in the vicinity of 0.8 MeV. All calculations using assignments of $1/2^+$, $3/2^+$, and $7/2^+$ resulted in elemental inelastic neutron scattering cross sections of ≈ 3 mb/sr at the incident neutron energies of interest here. Such small cross sections would not be definitively observed in these measurements. About 85% of the scattering from elemental Sn is due to the even isotopes, each having a 2^+ first excited state at ~ 1.2 MeV.²⁸ The calculated cross section of the element for the excitation of such a state was ~ 35 mb/sr, and the calculated scattered neutron spectrum was diffused over ~ 100 keV due to small energy differences in the excited structure of the contributing isotopes. Such a cross section is ~ 4 times the minimum sensitivity of the equipment and should have been easily observed when, in fact, only a qualitative identification was possible. Within a few hundred keV of threshold the excitation of these 2^+ states proceeds through a limited number of exit channels, and width-fluctuation corrections to the Hauser-Feshbach formula become important. Calculations were carried out using these corrections following the theory of Moldauer.²¹ The resulting calculated cross section for the excitation of the 2^+ state in Sn was < 21 mb/sr at an incident neutron energy of 1.4 MeV, or an observed cross section of ≈ 10 mb/sr in an ~ 50 -keV scattered neutron experimental resolution increment. This was twice the observed limit of a 4- to 5-mb/sr cross section, but the discrepancy could be attributed to the rapidly varying energy dependence of the detectors in the scattered neutron energy range from 200 to 300 keV.

The effect of the fluctuation correction is more evident from a comparison of calculated with experimental cross sections for inelastic scattering from Te (see Fig. 9). The principal contributions to the observed inelastic processes were due to the excitation of the first excited (2^+ , ~ 750 keV) states of the even isotopes Te^{126} , Te^{128} , and Te^{130} . The calculations were compared with experiment assuming the validity of the composite "model" shown in Fig. 9 with a ground state of 0^+ and a 750-keV 2^+ excited state. Hauser-Feshbach calculations resulted in an inelastic cross section (see solid line of Fig. 9) $\sim 30\%$ larger than the experimental values. Upon repeating the calculations, using the fluctuation correction of Moldauer, the dotted curve of Fig. 9 was obtained, in good agreement with experiment. The calculated cross sections for inelastic scattering from the odd-A isotope Te^{125} were < 4 mb/sr at energies of interest, a magnitude too small to be experimentally observed.

The element Mo is composed of no less than 7 isotopes of appreciable abundance. The odd-A isotopes 95 and 97 (total abundance 25%) have uncertain excited structure and little is known of Mo^{92} (see Ref. 28). The isotopic model of Fig. 11 and the optical potential giving the elastic scattering of Fig. 2 were used to carry out Hauser-Feshbach calculations of the inelastic excitation cross sections, with the results indicated by the solid lines of Fig. 6. The calculated excitation cross sections of the reactions with $Q = -0.2$ and -0.5 MeV were in agreement with experiment at incident neutron energies above ~ 0.8 MeV. At lower incident energies the experimental values tend to be larger than those calculated particularly for the excitation of the state at 0.2 MeV. The agreement between calculation and other reported experimental values is no better. A state has tentatively been assigned to Mo^{92} at an excitation energy of about 0.5 MeV.²⁸ Calculations were made assuming the spin and parity of this state was 2^+ . The resulting cross sections for the excitation of a 0.5-MeV "state" in the "model" element (see Fig. 11) were more than doubled and far larger than the observed experimental values. It was thus concluded that the tentatively reported 0.5-MeV state in Mo^{92} was not a 2^+ configuration if present at all. The observed inelastic excitation cross sections of Mo having $Q = -0.79$ MeV were assumed $\sim 80\%$ due to the 2^+ states of the even isotopes with an $\sim 10\%$ contribution from the odd isotopes (see Fig. 11). The latter were approximated by a single $7/2^+$ state. Hauser-Feshbach calculations with the above assumptions gave the solid curve in the upper portion of Fig. 6 and were $\sim 30\%$ larger than the present experimental values. This discrepancy could not be accounted for by reasonable variations in the configurations of the odd isotopes. Again, the application of the fluctuation correction brought the calculations into agreement with the cross sections determined in the present experiment and with those deduced from inelastic gamma-ray measurements.¹² As noted in Sect. 3, the inelastic excitation of a "state" in Mo at ~ 1.05 MeV was qualitatively observed. If a 2^+ spin and parity for such a state be assumed, the calculated excitation cross section was 4 mb/sr at an incident neutron energy of 1.4 MeV, in agreement with the observed

qualitative magnitude. However, possible inelastic scattering in this region ($Q \sim -1.05$ MeV) is confused by the contributions from the odd-A isotopes Mo^{95} and Mo^{97} .

The interpretation of inelastic scattering from elemental Sb (57%, 121; 43%, 123) was based on the reported level diagram of Fig. 12.²⁸ The spin and parity of the ground and first excited state are inverted in the two isotopes ($5/2^+$, $7/2^+$ for 121; and $7/2^+$, $5/2^+$ for 123). Only recently has the first excited state ($7/2^+$) in Sb^{121} been well resolved, and the reported 37-keV energy is in excellent agreement with that measured in the present work.²⁹ If a $7/2^+$ spin and parity for this state are assumed, the calculated cross section for its excitation with 560.0-keV incident neutrons was 399 mb, compared to the measured value of 300 ± 60 mb, tending to confirm the $7/2^+$ - $5/2^+$ first excited-ground state spin and parity assignments in Sb^{121} derived from the K/L ratio and other spectroscopic measurements.²⁸⁻³⁰ The calculated inelastic cross section of the 0.16-MeV ($5/2^+$) state in Sb^{123} compares favorably with the experimental values at incident energies greater than 0.6 MeV, but at lower incident energies the calculation tends to give results larger than the measured values (see Fig. 7). Assuming that $1/2^+$ and $3/2^+$ states in both isotopes of Sb contribute to the inelastic scattering with an observed $Q = -0.54$ MeV, the solid curve of Fig. 7 was calculated. This result is slightly smaller than the experimental values, but the latter were not well determined, as described above. By use of both $5/2^+$ or $7/2^+$ assignments for a state in Sb^{123} at ~ 1.1 MeV, the cross section for the inelastic cross section was computed. The resulting values were small ($7/2^+$ case is shown in Fig. 7), in accord with the marginal experimental observation of the respective inelastically scattered neutron group. A similar state near 1.1 MeV in Sb^{121} if present would have probably resulted in a cross section for the element that would have been clearly observed; thus it seemed unlikely that such existed.

5. SUMMARY

The results of these experiments provide an appreciably improved knowledge of the elastic and the inelastic scattering of neutrons from Mo, Sn, Sb, and Te throughout the incident energy range from 0.3 to 1.5 MeV. This increased experimental understanding made it realistic to examine the detailed behavior of an optical potential in the region of the closed proton shell at $Z = 50$. Such a potential employing surface absorption was shown to well describe the measured elastic scattering cross sections providing both the real and imaginary magnitudes (V and W) of the potential were varied as the closed proton shell at $Z = 50$ was traversed. The inelastic neutron scattering cross sections calculated from the Hauser-Feshbach formula compared reasonably well with the observed values providing width-fluctuation corrections were applied. These corrections were particularly important when associated with inelastic scattering from

Mo and Te. The spin and parity assignments reported in the literature were generally substantiated by the inelastic scattering measurements and the calculations, but with no verification of some tentative states in Sb^{121} and Mo^{92} . The observed elastic neutron scattering cross sections of, particularly, Te qualitatively indicated the presence of intermediate resonance structure.

ACKNOWLEDGMENTS

The authors are indebted to Drs. S. G. Buccino and D. Reitmann for their contributions to various portions of the work.

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