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FAST NEUTRON SCATTERING FROM Ta^{181}

by

A. B. Smith

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Reactor Engineering Division

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ABSTRACT

The spectrum of neutrons scattered from Ta^{181} was measured at incident neutron energies ranging from 0.3 to 1.5 Mev. Time-of-flight techniques were employed to resolve the elastically and the inelastically scattered components. The angular distribution of the elastically scattered neutrons was measured at $\lesssim$50-kev intervals with an incident spread of neutron energy of ~20 kev. Inelastically scattered neutron groups resulting in the excitation of residual nuclear levels at 140 ± 10, 300 ± 10, 620 ± 20, 725 ± 25, 900 ± 30, and 980 ± 30 kev were observed. The measurements indicated that the levels at 725 and 980 kev were composed of two or more components. In addition, inelastic scattering to a 480 ± 20-kev level was tentatively observed. The magnitudes of the differential elastic cross sections and of the inelastic excitation functions were determined relative to the known elastic scattering cross section of carbon. The experimental results were compared with those obtained in previous measurements and a qualitative comparison was made with theoretical calculations.

I. INTRODUCTION

A number of studies of the scattering of fast neutrons from Ta^{181} have been reported.(1-7) These experiments have not resulted in a comprehensive understanding of the various contributing processes. The experiments are difficult because of the complex structure of the odd-even Ta^{181} nucleus. Many inelastic exit channels are available, resulting in multiple inelastic neutron groups. Detection systems employing threshold devices generally do not provide sufficient resolution to separate the elastically scattered neutron group from the inelastic components. Moreover, threshold detectors yield only integral knowledge of the inelastic spectrum. An examination of gamma rays emitted following inelastic scattering can provide much insight into the structure of the residual nucleus. Such measurements do not uniquely determine the inelastic neutron scattering cross section, since the derivation of this quantity

from these measurements requires a knowledge of the internal conversion coefficients and of the branching ratios of the radioactive decay.

Theoretical interpretation of scattering from Ta^{181} is complicated by the deformation of this nucleus.(8) As a result, only a qualitative description can be expected from any theory based upon commonly employed spherical potentials.(9,10) Scattering from a nonspherical nucleus has been treated in only a limited number of instances, none of which is directly applicable to Ta^{181} in the energy range of this experiment.(11,12) The probability of direct interaction between the rotational modes of a deformed nucleus such as Ta^{181} and an incident neutron has been theoretically investigated.(12,13) Experimental evidence of such processes has not been obtained at neutron energies equivalent to those employed in this experiment.(14)

This study of Ta^{181} was performed as part of a comprehensive study of fast neutron scattering from intermediate and heavy nuclei. The results are of applied interest and it is hoped that they will help provide an experimental basis for theoretical understanding of an interesting nuclear region.

II. EXPERIMENTAL METHOD

A pulsed-beam, time-of-flight apparatus was employed throughout this experiment. The instrument used provided sufficient resolution to separate the elastically scattered neutron group from all inelastic components and to determine the spectrum of inelastically scattered neutrons. This equipment, described in detail elsewhere, was capable of producing a $\lesssim$5-ma current of protons at a target for ~1 nsec.(15,16) The pulse-repetition rate was variable up to 10 Mc per second. Neutrons were produced at the target by means of the $Li^7(p,n)Be^7$ reaction.(17) The lithium targets used were metal films ~20-kev thick. The resulting spread of neutron energy was sufficient to integrate many resonances in the tantalum scattering samples. Some of the source neutrons struck the sample located ~10 cm from the target, and were scattered over a distance of the order of a meter to the neutron detector.(18) The time between the target burst and the arrival of the scattered neutrons at the detector was measured, thus determining the scattered neutron energy. The relative energy sensitivity of the detector was calibrated with respect to a "long counter."(11,19) The sensitivity cutoff of the detector was $\lesssim$200 kev for most measurements. The source intensity was monitored with "long counters" so placed that they were not affected by changes in the scattering samples or in the placement of the time-of-flight detector.

All measurements were normalized relative to the known differential elastic scattering cross section of carbon.(7) The measured elastic scattering from carbon and the measured elastic and inelastic scattering from Ta^{181} were corrected for attenuation and multiple-scattering effects within the samples. A Monte-Carlo method was employed to carry out the multiple-scattering corrections.(15) The validity of this procedure was experimentally

verified by examining the energy distribution of neutrons multiply elastically scattered from a hydrogenous material and by experimentally determining the probability of double inelastic events.

All samples were right equilateral cylinders. They were struck on their lateral surfaces by the incident neutron beam. The sample sizes were such that the transmissions were $\gtrsim 75\%$. The tantalum sample was fabricated of natural metal consisting of $>99\%$ Ta^{181}. The differential elastic cross sections were usually measured at ten or more scattering angles between 20 deg-30 deg and 145 deg. The angular resolution was ~± 0.7 deg. The angular distributions of inelastically scattered neutrons were measured at similar angular intervals. In some instances, the inelastic excitation functions were so small that it was impracticable to carry out reliable measurements at many scattering angles. In these instances, the inelastic measurements were made at scattering angles of 45 deg, 90 deg, and 135 deg.

III. EXPERIMENTAL RESULTS

A typical experimental time distribution obtained at an incident neutron energy of 1400 kev is shown in Fig. 1. The figure abscissa is proportional to the flight time of the scattered neutrons and the ordinate denotes the relative response rate of the detector. The first neutron group to arrive at the detector following a source burst, to the far right in the figure, corresponds to neutrons elastically scattered from Ta^{181}. Slightly later in time, an inelastic neutron group corresponding to the excitation of a 140-kev residual nuclear state is noted in the figure. The next group recorded corresponds to the inelastic scattering to a 300-kev level. At a relative time position of 4.3 on the graph, a peak (n_2) corresponding to 940-kev neutrons is evident. A part of this group consists of those neutrons originating in the second component of the source reaction and subsequently elastically scattered into the detector.(17) However, the intensity of this peak is too large to be accounted for solely by this process. An inelastically scattered neutron group leading

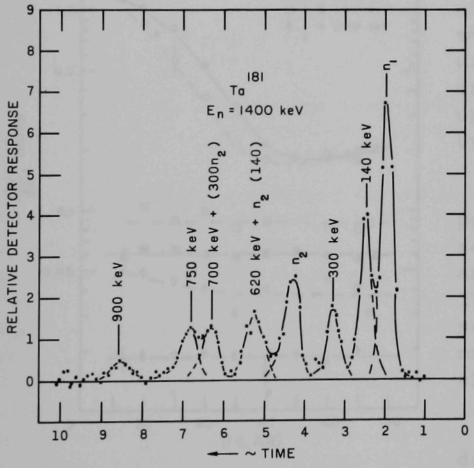

Fig. 1. An experimental time distribution resulting from the scattering of 1400-kev neutrons from Ta^{181}. Inelastic scattering to residual nuclear levels at 140, 300, 480, 620, 725, and 900-kev is evident.

to the excitation of a state at ~480 kev must be the remaining constituent of the peak. A group corresponding to inelastic scattering to a 620-kev state appears next in the figure. This group includes a small contribution from part of the second neutron source component which was inelastically scattered (Q = 140 kev). At a relative time position of 6.5 on the figure, two partially resolved neutron groups are evident. They correspond to inelastic scattering to nuclear levels at 700 and 750 kev. The former group must be slightly corrected for inelastically scattered neutrons (Q = -300 kev) from the second source group. The final inelastic group, at the far left of Fig. 1, corresponds to the excitation of a 900-kev level. The distribution shown in Fig. 1 is typical of many hundreds of experimental results.

By integrating the respective peaks of the measured time distributions and relating the resulting values to those obtained from similar measurements of elastic scattering from the carbon standard, the differential cross sections of Ta^{181} were obtained as a function of scattering and incident neutron energy. A typical result obtained at an incident neutron energy of 710 kev is shown in Fig. 2. The differential elastic cross section and the differential cross sections for the inelastic excitation of a 140-kev and a 300-kev level are evident. Both of the inelastic cross sections are isotropic within experimental accuracy. Measurements of these and other inelastic cross sections at various energies up to 1.5 Mev were all characterized by a similar isotropy.

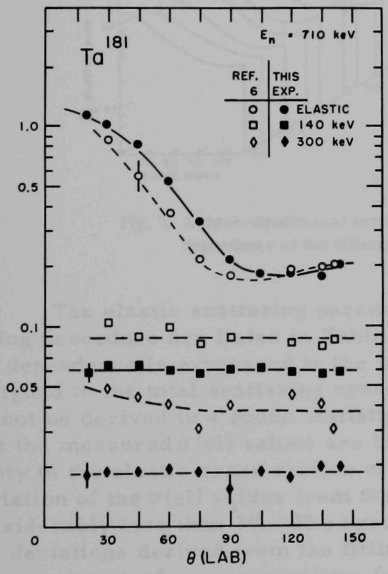

Fig. 2. The differential cross section for the scattering of 710-kev neutrons from Ta^{181}. The elastic cross section and the inelastic cross section for the excitation of the 140-kev and the 300-kev levels are shown.

The energy and angular dependence of the differential elastic scattering cross sections of Ta^{181} are qualitatively indicated in Fig. 3. The solid curves represent the cross sections obtained by fitting, using the method of least squares, the expression

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

to the experimental results. In this expression, σ(el) is the elastic scattering cross section and W_i represent the experimentally determined coefficients of the Legendre Polynomials P_i. The dotted curves shown in the figure are obtained in an analogous manner,

but refer to experimental measurements which include the first inelastic group (Q = -140 kev) with the elastic component. In reference to Fig. 3 it should be remembered that the fitting procedure is used to extrapolate the measured values forward from 20 deg and backward from 145 deg. Thus, some divergence occurs at the extreme angles, which is not truly representative of the experimental measurements.

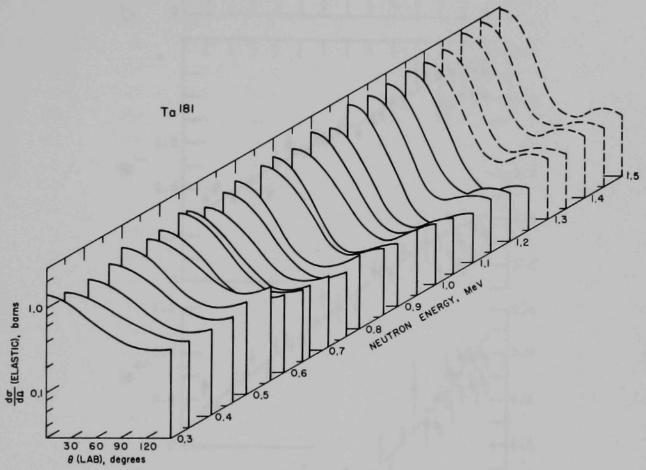

Fig. 3. A three-dimensional representation of the energy and angular dependence of the differential elastic cross section of Ta^{181}.

The elastic scattering parameters of Eq. (1) obtained from the fitting procedure are listed in Table I and illustrated in Fig. 4. All angular dependence is expressed in the laboratory system. No errors are assigned to the total scattering cross sections, since these uncertainties cannot be derived in a sound statistical manner. However, it is believed that the measured σ(el) values are known to ~7%, including an ~5% uncertainty in the elastic cross section of the carbon standard. The average deviation of the σ(el) values from the empirical line shown in Fig. 4 is considerably less than 7%. The errors given for the W_i values are standard deviations derived from the fitting procedure. As such, they are representative of errors resulting from a fit to a given experimental distribution, but they do not necessarily represent the actual experimental uncertainties. The relation of these errors to the empirical curves, shown in the figure, indicates that random experimental variations from energy to energy are not large.

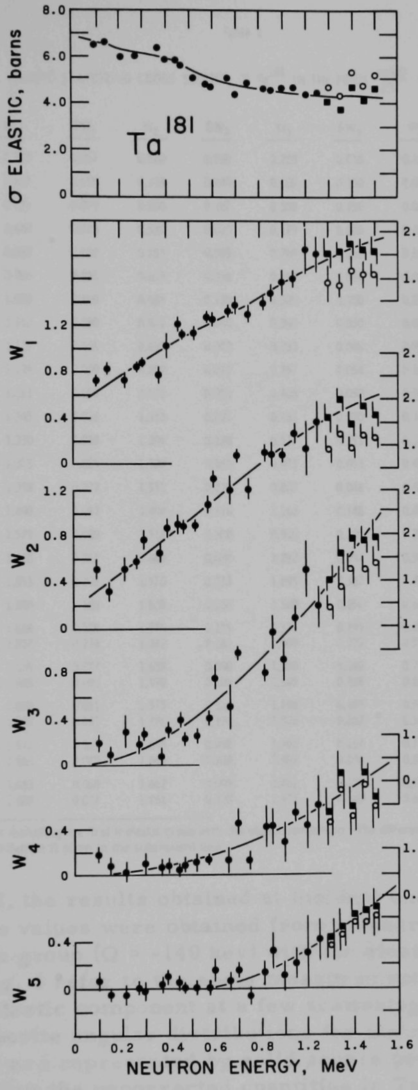

Fig. 4. The differential elastic cross section of Ta^{181} expressed in the form

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

Table I

THE DIFFERENTIAL ELASTIC SCATTERING CROSS SECTION OF Ta^{181} IN THE FORM $\frac{d\sigma(el)}{d\Omega} = \frac{\sigma(el)}{4\pi}\left[1 + \sum_{i=1}^{5} W_i P_i\right]$

E_n(kev)	σ_t(b)	W_1	δW_1	W_2	δW_2	W_3	δW_3	W_4	δW_4	W_5	δW_5
300	6.48	0.729	0.017	0.520	0.020	0.223	0.038	0.171	0.031	0.070	0.048
350	6.65	0.835	0.050	0.313	0.040	0.100	0.150	0.080	0.100	-0.050	0.100
415	5.98	0.726	0.072	0.536	0.107	0.300	0.150	0.010	0.050	-0.060	0.100
475	5.99	0.844	0.030	0.585	0.030	0.179	0.040	0.009	0.010	0.010	0.010
500	7.07(?)	0.880	0.030	0.783	0.045	0.269	0.061	0.102	0.066	-0.031	0.061
570	6.31	0.760	0.035	0.653	0.056	0.089	0.064	0.060	0.070	0.037	0.060
600	5.79	1.030	0.060	0.885	0.110	0.325	0.100	0.085	0.100	0.101	0.100
650	5.89	1.210	0.060	0.901	0.040	0.390	0.050	0.044	0.050	0.053	0.050
670	5.55	1.125	0.003	0.895	0.042	0.233	0.046	0.086	0.060	0.001	0.020
720	5.09	1.129	0.030	0.889	0.027	0.267	0.054	0.105	0.090	0.000	0.050
775	4.81	1.261	0.050	1.070	0.050	0.408	0.050	0.140	0.050	0.000	0.050
800	4.72	1.245	0.016	1.314	0.023	0.761	0.030	0.329	0.033	0.167	0.033
870	5.10	1.330	0.040	1.205	0.120	0.517	0.153	0.114	0.150	0.050	0.100
900	4.32	1.378	0.029	1.500	0.042	0.971	0.053	0.450	0.059	0.161	0.061
1020	4.69	1.398	0.032	1.531	0.050	0.807	0.048	0.400	0.063	0.147	0.090
1050	4.50	1.490	0.082	1.498	0.116	1.166	0.148	0.413	0.164	0.332	0.168
1100	4.64	1.579	0.080	1.514	0.100	0.910	0.100	0.273	0.120	0.109	0.120
1150	4.67	1.600	0.051	1.689	0.070	1.282	0.092	0.539	0.101	0.202	0.101
1200	4.25	1.853	0.200	1.570	0.283	1.693	0.367	0.416	0.363	0.300	0.300
1250	4.38	1.820	0.180	1.800	0.200	1.380	0.250	0.607	0.300	0.426	0.300
1300[a]	4.66	1.566	0.108	1.575	0.155	1.376	0.191	0.454	0.197	0.367	0.176
	3.98	1.832	0.126	1.842	0.181	1.609	0.223	0.531	0.230	0.429	0.205
1350[a]	4.20	1.539	0.077	1.683	0.090	1.556	0.142	0.746	0.129	0.445	0.162
	3.54	1.825	0.091	1.990	0.106	1.845	0.168	0.884	0.154	0.527	0.192
1400[a]	5.30	1.675	0.081	1.575	0.116	1.736	0.143	0.518	0.148	0.568	0.132
	4.67	1.899	0.091	1.786	0.131	1.968	0.162	0.587	0.167	0.644	0.149
1450[a]	4.65	1.613	0.063	1.695	0.090	1.703	0.114	0.777	0.127	0.575	0.130
	4.05	1.851	0.072	1.945	0.104	1.955	0.130	0.891	0.146	0.660	0.149
1500[a]	5.11	1.643	0.069	1.662	0.099	1.761	0.125	0.594	0.139	0.629	0.143
	4.56	1.840	0.077	1.861	0.110	1.972	0.140	0.664	0.155	0.704	0.160

[a]Denotes measurements including the first inelastic group with the elastic component. The differential elastic cross section corrected for this contribution is given in the subsequent line.

In Table I, the results obtained at incident energies above 1250 kev are noted. These values were obtained from measurements which included the first inelastic group ($Q = -140$ kev) with the elastic component. The open points in Fig. 4 refer to the same measurements. Careful measurements of this inelastic component at a few scattering angles were used to correct the composite angular distributions for their inelastic content. The corrected values are represented by solid square points in Fig. 4 and are noted directly below the uncorrected quantities in Table I. All results given in Table I and Fig. 4 have been corrected for multiple scattering effects.

The nuclear structure of Ta^{181} observed in this experiment is shown in Fig. 5 along with that reported in the literature.[3,5,20-27] The observed

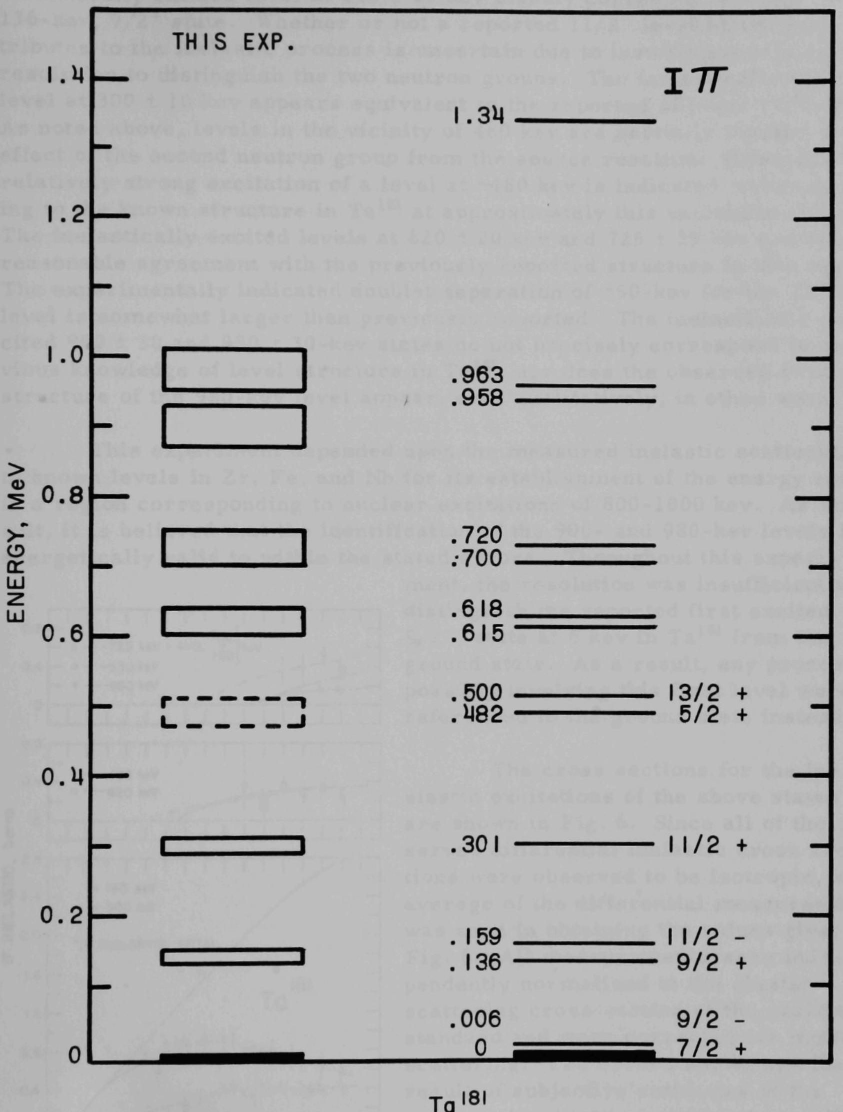

Fig. 5. The level structure of Ta^{181} as obtained from this experiment compared with that reported in the literature. The widths of the boxes represent the energy uncertainties in this experiment.

inelastically excited level at 140 ± 10 kev closely corresponds to the known 136-kev, 9/2$^+$ state. Whether or not a reported 11/2$^-$ level at 158 kev contributes to the inelastic process is uncertain due to insufficient experimental resolution to distinguish the two neutron groups. The inelastically excited level at 300 ± 10 kev appears equivalent to the reported 301-kev 11/2$^+$ state. As noted above, levels in the vicinity of 480 kev are partially masked by the effect of the second neutron group from the source reaction. However, a relatively strong excitation of a level at ~480 kev is indicated, corresponding to the known structure in Ta^{181} at approximately this excitation energy. The inelastically excited levels at 620 ± 20 kev and 725 ± 25 kev are in reasonable agreement with the previously reported structure in this region. The experimentally indicated doublet separation of ~50-kev for the 725-kev level is somewhat larger than previously reported. The inelastically excited 900 ± 30 and 980 ± 30-kev states do not precisely correspond to previous knowledge of level structure in Ta^{181}, nor does the observed doublet structure of the 980-kev level appear, even qualitatively, in other work.

This experiment depended upon the measured inelastic scattering to known levels in Zr, Fe, and Nb for its establishment of the energy scale in a region corresponding to nuclear excitations of 800-1000 kev. As a result, it is believed that the identification of the 900- and 980-kev levels is energetically valid to within the stated errors. Throughout this experiment, the resolution was insufficient to distinguish the reported first excited, 9/2$^-$, state at 6 kev in Ta^{181} from the ground state. As a result, any processes possibly involving this first level were referenced to the ground state instead.

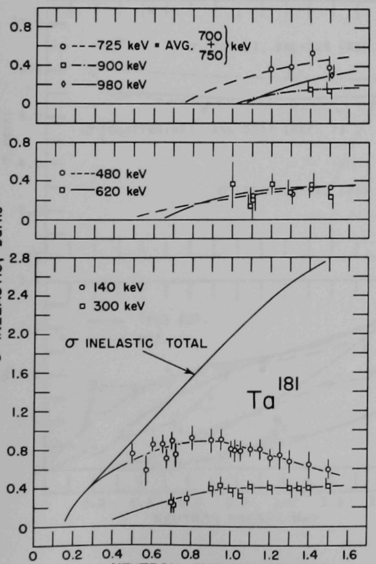

Fig. 6. The measured inelastic excitation functions of Ta^{181}.

The cross sections for the inelastic excitations of the above states are shown in Fig. 6. Since all of the observed differential inelastic cross sections were observed to be isotropic, an average of the differential measurements was used in obtaining the values given in Fig. 6. All measurements were independently normalized to the elastic scattering cross section of the carbon standard and were corrected for multiple scattering. The errors shown are the result of subjective estimates of the measured accuracy and include an ~5% error assigned to the cross section of the carbon standard. The measured cross sections for the excitation of 140-, 300-, 900-, and 980-kev levels were usually resolved and not perturbed by the second source neutron group.

However, due to the presence of the second source group, small corrections were necessary in the measured cross sections for scattering to the 700- and 620-kev levels. The ratio of the probability of excitation of the 700-kev level to that of the 750-kev level was estimated to be ~0.75 at a 1400-kev incident neutron energy. In Figs. 5 and 6 these two neutron groups are treated as a single component leading to an "effective" level at 725 ± 25 kev. Similarly, what appears to be a multiple level structure at 980 kev is treated as a single "effective" level at 980 ± 30 kev in both Figs. 5 and 6. The 480-kev excitation function shown must be considered only qualitative since, at all times, the measurements included a sizeable contribution from the second source neutron group. Knowing the respective elastic cross sections and the relative abundance of the second source group, corrections for the second source group contribution were made.[28] In view of these corrections, the accuracy of the measured cross section for the excitation of the 480-kev level is estimated at ±50%.

The quantitative measurement of the excitation functions was terminated ~300 kev above the respective thresholds. Although the detector response extended down in energy to ≲200 kev, it was believed that the region from 200-300 kev was too sensitive to shifts in detector response to permit good quantitative measurements. The solid curves in Fig. 6 are empirical and are meant to delineate the energy dependence of the experimental results. They have no a priori relation to the theory. The total inelastic cross section of Ta^{181}, as determined by summing the individual components, is also shown in Fig. 6.

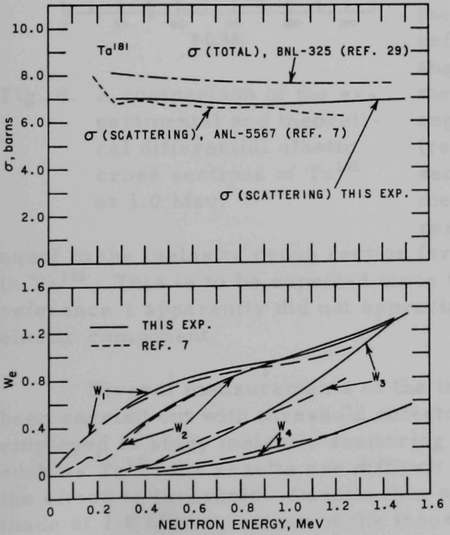

Fig. 7. A comparison of the measured differential total scattering cross sections of Ta^{181}.

IV. DISCUSSION

The differential elastic and inelastic cross sections determined in this experiment were combined to obtain the differential total scattering cross section. The result is compared with the measurements of Langsdorf et al. in Fig. 7.[7] The agreement between the two measurements is reasonably good in both magnitude (σ scattering) and angular dependence [described in form of Eq. (1) above]. Figure 7 also shows the total cross section of Ta^{181} as reported in BNL-325.[29]

The latter is not in particularly good agreement with the results reported in reference 7 nor with those obtained from this experiment, the differences being far too great to be reasonably accounted for by the capture cross section.

Previous measurements of the microscopic scattering cross sections for Ta^{181} are not plentiful.(1,6) The results of one such measurement are indicated by open points in Fig. 2.(6) The elastic and inelastic differential cross sections are given at an incident neutron energy of 710 kev. As is evident in Fig. 2, the inelastic cross sections obtained in the present experiment are appreciably lower than those given in reference 6. Moreover, the elastic cross section reported in reference 6, does not agree with the results of this experiment in either shape or magnitude. Multiple scattering effects, possibly not corrected for in the previous work (reference 6), may be a contributing factor to this discrepancy.

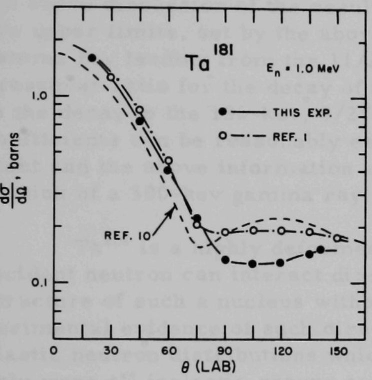

Fig. 8. A comparison of the experimental and theoretical differential elastic cross sections of Ta^{181} at 1.0 Mev.

The elastic cross section at 1.0 Mev resulting from this experiment is shown with that reported in reference 1 in Fig. 8. At forward angles the agreement between the two measurements is good. At backward angles the previous measurements (reference 1) lead to a larger cross section than that found in this experiment. The difference between the two results shown in Fig. 8 is essentially equal to the inelastic cross section for the excitation of the 140-kev level in Ta^{181}. This is to be expected since the "elastic" measurements of reference 1 apparently did not appreciably discriminate against this inelastic component.

Several measurements of the inelastic cross section of Ta^{181} have been carried out with threshold detectors.(1,2,30) When this technique is employed to study inelastic scattering from nuclei having low-lying levels, such as Ta^{181}, the results are difficult to interpret due to uncertainties in the effective threshold. Despite this problem, the results of measurements made at 1.0 Mev by means of the threshold method are in qualitative agreement with those obtained in this experiment.(1)

Studies of gamma rays emitted in the n-n'γ process do not result in unique determinations of the inelastic cross sections, since a knowledge

of internal conversion, branching ratios, and nuclear structure are requisite. However, studies of the inelastic excitation of a 136-kev gamma ray do lead to cross sections for inelastic scattering in qualitative agreement with the cross section for the excitation of the 140-kev state obtained in this experiment.(3)

Recent gamma-ray measurements reported by Lind and Day are more difficult to relate to the results of this experiment.(4,5) These authors report a relatively large cross section for the excitation of a 480-kev gamma ray leading to the ground state. This result is reasonable in the context of the above discussion of the results of this experiment. However, the very low upper limits, set by the above authors, on the intensity of a 300-kev gamma ray leading from the $11/2^+$ state to the ground state is puzzling. The crossover ratio for the decay of the $11/2^+$ level to the ground state relative to the decay to the 136-kev, $9/2^+$ level is known, and the internal conversion coefficients can be reasonably estimated.(26,31) If the results of this experiment and the above information are employed, the cross section for the production of a 300-kev gamma ray should be 5-10 times that reported.(5)

Ta^{181} is a highly deformed nucleus.(9) It has been shown that an incident neutron can interact directly with the characteristic rotational structure of such a nucleus without forming a compound state.(12,13) Experimental evidence of such direct interactions may take the form of inelastic neutron distributions which are not symmetric about 90 deg. Not only were all inelastic groups experimentally observed in this experiment symmetric about 90 deg, but they were also isotropic (see Fig. 2, for example). This isotropy indicates that, at the energies employed in this experiment, direct interaction mechanisms do not play a significant part in the inelastic scattering of fast neutrons from Ta^{181}.

Several authors have employed Hauser-Feshbach formalism to interpret elastic scattering from a wide range of elements.(8) The results obtained from one such calculation, as applied to Ta^{181}, are shown in Fig. 8.(10) The same figure shows the elastic distribution as measured in this experiment and that previously reported.(1) In this particular calculation (reference 10), a nonlocal potential and a spin-orbit term were used. Compound elastic scattering is included in the curve shown in Fig. 8. The theoretical agreement with either of the experiments is only qualitative. Better agreement cannot really be expected until the theoretical methods employed take proper cognizance of the non-spherical nature of the Ta^{181} nucleus. It is hoped that improved experimental understanding of scattering from deformed nuclei such as Ta^{181} will encourage further theoretical study of this important class of nuclei.

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