SPECTRA OF γ -RAYS FROM CAPTURE OF 2 eV TO 9 X 10⁴ eV NEUTRONS BY ¹⁸¹Ta

Marion Lee Stelts
(Ph. D. Thesis)

Prepared for U.S. Energy Research & Development
Administration under contract No. W-7405-Eng-48

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Printed in the United States of America
Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy \$ *; Microfiche \$2.25

<u>* Pages</u>	<u>NTIS Selling Price</u>
1-50	\$4.00
51-150	\$5.45
151-325	\$7.60
326-500	\$10.60
501-1000	\$13.60

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UCRL-51907

**SPECTRA OF γ -RAYS FROM CAPTURE OF 2 eV TO
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Abstract

Using new experimental techniques, the spectra of γ -rays from the capture of neutrons by ^{181}Ta were measured at the Livermore 100-MeV linac for neutrons from 2 eV to 9×10^4 eV with a (Ge(Li)-NaI) three-crystal spectrometer. Individual primary γ -ray lines were resolved to 1778-keV excitation in ^{182}Ta . Neutron resonances were resolved to 200-eV neutron energy. Data analysis techniques and codes were developed to extract positions and intensities of resolved transitions from the large data matrices accumulated in this experiment. Techniques were developed to unfold the unresolved γ -ray spectra using the simple response of the three-crystal spectrometer. The resolved transition data were used to place 110 states with spin and parity assignments in the ^{182}Ta level diagram below 1780-keV excitation. A set of 1240 E1 transition strengths were analyzed to extract 1.38 ± 0.11 degrees of freedom for the most likely chisquared fit to the distribution of widths. The E1 strength function was extracted for $E_\gamma = 4$ to 6 MeV and compared with previous results. The γ -ray spectra for $E_\gamma = 1.5$ to 6.1 MeV were unfolded for neutron energy groups between 20 and 9×10^4 eV. Below 5-MeV γ -ray energy no dependence of the spectral shape on neutron energy was observed.

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Acknowledgements

A large number of people have contributed their support, knowledge and encouragement to the author during the course of this research project. I would like to thank the electronic engineering support group and the mechanical shop staff for their assistance in preparing the equipment used in this experiment, and the accelerator staff for smooth operation of the linac during the course of the data collection.

In particular I would like to thank my wife, Ramie, and two boys, Steven and Timothy for their encouragement and patience, and Dr. John C. Browne for guidance, discussions, help with data collection and patient proofreading of this thesis.

I. Introduction

If a neutron of kinetic energy E_n is captured by a heavy nucleus such as ^{181}Ta , a capture state of excitation, $E_n + E_n'$, is formed where E_n' is the binding energy of the neutron in the compound nucleus. The nucleus can deexcite by emission of a cascade of electromagnetic radiation proceeding through states of lower excitation until the ground state is reached. Typically, three to five γ -rays are emitted in each capture event.

The γ -ray spectrum displays discrete lines at γ -ray energies near the excitation of the compound system merging into a continuum of increasing intensity as the γ -ray energy decreases. Discrete lines again become apparent at γ -ray energies of less than a few MeV.

These components of the spectrum arise from several sources. The low-energy lines are due to deexcitation of low-lying states at the end of the cascade process. They show minor intensity variations as different capture states are populated. The high-energy lines are due to primary transitions from the capture state to low-lying levels. These transitions show marked intensity variations, as a function of the capture state, due to fluctuations in the matrix elements connecting the capture and final states. These fluctuations can be reduced by averaging over a sufficient number of capture states. The observed continuum at intermediate γ -ray energies is due to an increasing level density in the residual nucleus and a finite instrumental resolution.

The character of the high-energy radiation is dipole with the average intensity of the electric dipole (E1) transitions approximately ten times as strong as the magnetic dipole (M1) transitions. Higher order transitions are orders of magnitude less intense. The energy dependence of electric dipole radiation is proportional to E^n where n is between three and five.¹⁻³ Consequently the high energy lines are primary γ -rays and there is a one to one correspondence between the final state excitation energy and the γ -ray energy. If the capture state spins and parities are known, the dipole selection rules and the intensity difference between E1 and M1 radiation allows parity assignments and spin determinations to be made for those final states accessible from the capture states.

The majority of neutron capture γ -ray spectra have been measured at thermal neutron energies. In general, the compound system will not be in a well-defined nuclear state at thermal energy, but will be composed of the tails of nearby bound and unbound states. At slightly higher neutron energies, resonances due to population of states of well-defined spin and parity appear in the capture cross section. As the neutron energy increases further, the observed resonances begin to overlap due to doppler broadening and decreased instrumental resolution to form a continuum.

The maximum information on spectroscopic properties of the final states, the distribution of partial radiation widths and average spectral properties, can be obtained by studying the intensities of primary γ -ray lines for the resolved resonances which have known spins and parities. However the unresolved

region can also be analyzed for multipolarity and average strengths of transitions as well as averaged γ -ray spectral properties by summing the spectra over a sufficient range of neutron energies to include many initial states.

For a heavy nucleus such as ^{182}Ta at high excitation energies, a statistical model of the nucleus assumes that the wave functions are complicated and uncorrelated. The matrix elements connecting the capture and final states will then have a normal distribution about zero mean value. Therefore the partial radiation widths should be distributed with a chisquared distribution having one degree of freedom. Values observed in previous experiments on heavy nuclei range from 0.7 to 4 degrees of freedom.^{1,2,4,9-15} The distribution of partial widths for ^{182}Ta was examined in this experiment to test this statistical hypothesis.

For a given nucleus, the average intensity for an E1 transition can be expressed in terms of the E1 strength function. The Brink-Axel^{2,6} hypothesis predicts a shape and magnitude for the strength function based on an extrapolation of the E1 giant resonance to low γ -ray energies. This hypothesis was based on considerations of detailed balance and the assumption that each excited nuclear state has a giant dipole resonance built upon it, identical in shape and magnitude to the ground state giant resonance, but shifted by the excitation energy. This hypothesis was tested directly for ^{182}Ta by measuring the absolute intensity of resolved primary E1 transitions in the γ -ray energy region of 4 to 6 MeV.

It is also possible to extract a strength function even where individual transitions cannot be resolved by measuring the spectral intensity. This requires the additional knowledge of the level density of the compound nucleus at all excitations up to the binding energy. It is also necessary to unfold the experimental data using the detector response function. The average spectra were unfolded to yield spectral data in the 1.5 to 6.1 MeV energy region.

The reaction $^{181}\text{Ta}(n,\gamma)^{182}\text{Ta}$ was studied with a three-crystal (Ge(Li)-NaI) spectrometer at the Livermore 100-MeV electron linear accelerator (linac) to provide data to test these hypotheses and study the level structure of ^{182}Ta . The three-crystal spectrometer provides a clean, high-resolution response that is useful for resolving lines in complicated spectra. It also has a simple response as a function of γ -ray energy, which can be rather easily unfolded from unresolved spectra.

The capture γ -ray spectra from the capture of neutrons by ^{181}Ta have been studied previously by several workers¹⁵⁻²¹ using a variety of techniques. Much of the work has been done at thermal neutron energy. The one experiment in the resolved resonance region¹⁵ used a single-crystal Ge(Li) detector with a reactor with a mechanical chopper as the neutron source. An insufficient number of resonances were resolved to make a definitive determination of the final state spins and parities. The work which contributed the most spectroscopic information^{16,17} was done with a 2-keV filtered reactor beam with sufficient energy width to average over many resonances. This work was also done with a single Ge(Li) crystal.

In the present experiment, by utilizing the excellent neutron energy resolution of the linac time-of-flight facility and the simple response of the three-crystal Ge(Li) spectrometer, the range of measurement of the capture gamma ray spectra was increased in both excitation energy and neutron energy to provide more definitive spectroscopic information on ^{182}Ta . This wider range of data allowed a more accurate measurement of the distribution of partial widths and the E1 strength function. Finally, by unfolding spectra averaged over many resonances, the behavior of the spectral shape as a function of incident neutron energy was also obtained.

The averaged spectral data as a function of neutron energy can be applied to problems of radiation transport and shielding for reactors and military applications. The extracted parameters on level density and strength functions contribute to the body of knowledge necessary to reliably calculate these spectra from nuclear models.

II. Experimental Techniques

The object of this experiment was to measure the spectra of γ -rays from the capture of 2-eV to 10^5 -eV neutrons by ^{181}Ta , resolving, where possible, individual resonances in the capture cross section. It was thus necessary to measure simultaneously the energy of the neutron initiating an event and the photon spectra arising from the capture reaction. The photon spectra were measured with high-resolution Ge(Li) diode detector systems. These detector systems and spectra will be described in detail in later sections. The energies of the neutrons were determined by measuring the time-of-flight of the neutrons from the pulsed neutron source of the Livermore 100-MeV electron linear accelerator to the ^{181}Ta sample located 13.4 m away.

The experimental facility is shown in Figure 1. The linac and the experimental area shown are in a cave located 8 m below ground level. The electron beam from the linac enters from the lower right of the figure and is focused on the neutron-producing target at the upper center of the figure. The linac produces electron bursts 5 to 3000 nsec long at energies from 10 to 150 MeV and at repetition rates up to 1440 Hz. In this experiment typical electron beam parameters were 100 MeV energy, 30 nsec burst, 720 Hz repetition rate, and 75 μA average current. The energy and beam width parameters were chosen to optimize counting rate and resolution. The energy range of the neutrons produced by the electron pulse extends from above 10 MeV to thermal energies. Due to the long flight times for slow neutrons, the repetition rate had to be limited and the slow neutrons absorbed to prevent them from interfering with the

neutrons from subsequent beam pulses. This was done by placing a 0.5 mm sheet of cadmium in the neutron beam. The high absorption cross section of cadmium below 0.5 eV removed the slow neutrons. The repetition rate was limited to 720 Hz so that the time between beam pulses corresponded to the flight time of 0.5 eV neutrons for this experiment.

The neutron-producing target is a 41 x 41 x 57 mm stack of water-cooled Ta plates in a stainless steel can. The neutrons are produced by a multistep process where part of the electron energy is converted to photons via the bremsstrahlung process upon striking the tantalum. These photons interact with the Ta nuclei to produce neutrons via the (γ, n) , (γ, np) , $(\gamma, 2n)$, etc., processes. The time for this sequence of events to occur is less than 10^{-10} seconds. The neutrons produced have a Maxwellian energy distribution with a temperature of ~ 1 MeV. The target is surrounded by a moderator to reduce the energies of the emitted neutrons and thus maximize the flux in the energy range of interest for the experiment.

The moderator consists of two water-filled stainless steel cans which, when placed around the neutron target, form a 10-cm cube with the target at the center. The cans have 0.5-mm walls. Water from a closed loop cooling system is circulated through the moderator to prevent loss of water by heating and evaporation.

The integrated neutron flux produced over the 4π solid angle is $\sim 2 \times 10^{12}$ neutrons/sec per kilowatt of beam power. For the energy range 1 to 10^5 eV the shape of the moderated spectrum is well represented by an $E_n^{-0.9}$ energy dependence.

The neutron beam was defined by five 25-cm long boric acid collimators placed in an evacuated flight tube extending from the neutron-producing target to the sample, 13.4 meters away (see Figure 1). The collimator dimensions were chosen to subtend the entire moderator and target assembly when viewed from the sample, producing a beam size of 50 x 100 mm at the sample. (The sample and detector system were protected from indirect neutrons by two shielding walls totaling 4.6-m thickness.) A 5-cm lead collimator was placed at the end of the evacuated flight tube to shield the detector from γ -rays produced in upstream collimators.

The entrance and exit windows for the flight tube were 0.5 mm aluminum. At the gap in the flight tube between the shielding walls, where various beam filters were placed, there were 0.25 mm mylar windows. When needed, a 40-cm long Pb shadow bar, to prevent γ -rays produced in the neutron target from striking the sample, was placed between the target and the beginning of the flight tube. To reduce backgrounds, an evacuated tube was placed behind the sample to allow the neutron beam to pass into a 2-m deep hole in the concrete wall and thus be absorbed as far as possible from the detector.

Natural Ta (99.988% ^{181}Ta) samples were mounted on an aluminum rod placed in a styrofoam block. The samples were oriented so there was an 18° angle between the normal to the foil and the beam direction. The foil-detector orientation was such that the low energy γ -rays from the electron burst (γ -flash) would have to pass through the foil while scattering before striking the detector which was oriented at 90° with respect to the neutron beam direction.

The time-of-flight of the neutron initiating each capture event was measured using the following procedure. For each beam burst an accurate clock was started with a pulse derived from the electron current pulse striking the neutron-producing target. Since the capture state has a lifetime of the order of 10^{-14} seconds, the time of the event, T_e , can be recorded relative to the current pulse by deriving a timing signal from the detection of the primary γ -rays deexciting the capture state. The absolute time-of-flight of the neutron, T_n , over the flight path, L , was obtained by noting the time-of-arrival of the γ -flash, T_γ , at the detector. The time-of-flight was then calculated with the expression,

$$T_n = T_e - T_\gamma + L/c, \quad (1)$$

where c is the velocity of light.

The velocity of the neutron, V_n , for nonrelativistic neutrons is $V_n = L/T_n$, and thus

$$E_n = \frac{1}{2} m_n V_n^2 = \frac{m_n c^2 L^2}{2c^2 T_n^2}. \quad (2)$$

If T_n is measured in μsec , and L in m , then

$$E_n (\text{eV}) = 5227 L^2 / T_n^2. \quad (3)$$

The resolution of this experiment was affected primarily by uncertainties in the flight path, ΔL , and by the width of the time bin, ΔT , in which the event was stored. The widths of the time channels ranged from 32 to 8192 nsec and 256 to 8192 nsec for the two sets of channel widths used in this experiment. For

the region of resolved resonances the channel width was typically 256 nsec. The detector timing resolution was about 10 nsec full-width-half-maximum. The resolution broadening due to the neutron moderation time was less than the time channel widths for all energies of the experiment. The electron beam pulse width ranged from 20 nsec to 100 nsec for the different sets of data and was not included in the calculation of the resolution. From eq. (2),

$$|\Delta E_L| = 2E_n \Delta L/L \quad (4)$$

and

$$|\Delta E_T| = 2E_n \Delta T/T. \quad (5)$$

If these uncertainties are added in quadrature, the total resolution is

$$\left| \frac{\Delta E_n}{E_n} \right| = 2 \sqrt{(\Delta T/T)^2 + (\Delta L/L)^2}. \quad (6)$$

Limitations on the data storage space necessitated limiting the total number of time channels to ~620. The time channel widths were then chosen to give a resolution of <2% in the region where resolution is most important for resolving individual resonances.

The total resolution for each of the two sets of channel widths used in the experiment is shown in Figure 2. An uncertainty of ± 25 mm was assumed for the flight path. The dashed line shows the time-of-flight for neutrons vs neutron energy for a flight path of 13.42 m.

Sample thicknesses ranging from 0.15 mm to 2.5 mm were used in this experiment. These samples were all "black" for the low-

energy resonances. That is, the cross sections near the peaks of the resonances are so large that with these sample thicknesses, all neutrons with energies near the peak interacted with the sample. Since the spectra, rather than the absolute cross sections, were to be measured, this was not important. For background determinations the Ta sample was replaced with a carbon foil which gave the same scattering as the Ta sample at 10-keV neutron energy. Backgrounds resulting from out-of-time neutrons were also measured by placing "black" absorbers of Au, Mn, and Al in the beam to produce "holes" in the flux at 4.9, 337, 2360, and 35200 eV.

Figure 3 shows the counting rate as a function of neutron energy for γ -rays between 2.4 and 6.1 MeV. Below 200 eV most resonances are resolved; the spectrum evolves into a continuum at higher energies.

A. Detectors

As mentioned above, the object of this experiment is to measure γ -spectra from the capture of 2- to 10^5 -eV neutrons on tantalum. Since the Q-value of the $^{181}\text{Ta}(n,\gamma)^{182}\text{Ta}$ reaction is 6.063 MeV, this requires measurement of gamma intensities to 6.1 MeV gamma energy. The lowest energy portion of the spectra consists of lines of well-defined energy arising from the deexcitation of low-lying levels in ^{182}Ta . The highest energies arise from primary transitions from the capture state to the low-lying states. See Figure 4. These kinds of transitions are indicated respectively on the right and left-hand sides of the level diagram shown in Figure 4. The spacing of the capture states is of the order of 4 eV at the binding energy. For incident neutron energies below 100 eV most of these states can be resolved by the neutron time-of-flight method. The spacing of the low-lying states in the residual nucleus is of the order of 40 keV. Germanium diodes²²⁻²⁸ have resolutions of about 1 to 6 keV as the γ -ray energy varies from 100 keV to 6 MeV and are therefore suitable for resolving individual transitions in these two regions.

For γ -rays in the energy range 2-4 MeV, the level density of the residual nucleus is too large for even germanium detectors to resolve individual transitions (Figure 4). To extract averaged spectral information in this region the detector should have the simplest possible response function. A detector with a simple response is defined as one which has as large a component as possible approximating a delta function in γ -energy and as small as possible continuum response. Germanium diodes can be

used to approximate this response at high energies by the "three-crystal spectrometer" technique which emphasizes the double-escape peak response. This will be explained in more detail in the following discussion.

A Ge(Li) detector^{22,23} is essentially a diode constructed of n-type germanium with Li drifted into the detector to compensate for impurities and thus form a volume of "compensated" germanium. The diode is etched with hydrofluoric acid to clean the surfaces, placed in a clean vacuum system, and cooled to liquid nitrogen temperatures. A reverse bias voltage (typically 2000 V per cm of drifted germanium) is applied. Under these conditions virtually no current ($< 1 \times 10^{-9}$ A) flows through the diode. When radiation interacts with the active volume, ion pairs are produced. On the average, it takes 2.96 eV to create each ion pair. The applied field sweeps this charge out of the diode. By measuring the charge collected, the energy deposited by the radiation can be determined.

In the energy region, 100 keV to 10 MeV, γ -rays interact with Ge via the photoelectric, Compton scattering and pair-production processes. Figure 5 shows these interaction coefficients for this energy range.²⁹ The photoelectric process dominates below 150 keV and the pair-production above 8 MeV. At intermediate energies the Compton cross section is predominant.

Figure 6 schematically shows the response of a diode of volume 17.6 cc to monoenergetic 2500-keV photons. The continuum from 0 to 2300 keV results from Compton processes where the γ -ray scatters from a quasifree electron at some angle. The energy given to the electron varies from 0 to 2300 keV as the scattering

angle goes from 0 to 180° . The peak at 2500 keV is the full energy peak (FEP). From Figure 5 this cannot be due solely to the photoelectric process where the γ -ray gives all its energy to a bound electron but is, in fact, due to multiple interactions which result in the total absorption in the detector of the γ -ray energy. The peaks at 1989 and 1478 keV are due to the single-escape peak (SEP) and double-escape peak (DEP) respectively. These arise when the photon interacts with the detector through the pair-production process. As the electron-positron pair stops in the crystal, $E - 2mc^2$ is deposited. The positron then annihilates with an electron and emits two oppositely-directed 511-keV photons. If both quanta escape the detector without interaction, the total energy deposited is 1478 keV and the event is registered in the DEP. If one is absorbed and the other escapes, 1989 keV is deposited and the event registered in the SEP. If both quanta are absorbed, all the energy is deposited and the event falls in the full-energy peak.

An important criterion in the performance of Ge(Li) diodes is the ratio of the peak counts to the continuum. The more the peak stands out relative to continuum events, fewer peak counts are needed for the peak to be statistically valid. For all energies, the better the resolution, the better the peak will stand out. For γ -ray energies below a few MeV the FEP can be enhanced relative to the rest of the events by increasing the detector size and thus the probability of multiple interactions. For higher energies it is not currently feasible to fabricate detectors with large enough volumes to overcome the unfavorable ratio of Compton to photoelectric cross sections.

If, at higher energies, we choose to analyze the double-escape peak rather than the full-energy peak another technique is available. By choosing the detector to be of modest dimensions, we can enhance the escape of the annihilation photons and thus emphasize the DEP. A further reduction of the continuum can be accomplished by detection of both annihilation quanta and by requiring a triple coincidence between both annihilation detectors and the Ge(Li) diode. This is the three-crystal spectrometer technique.^{23,24}

The resolution of a detector system as a function of energy is determined primarily by two effects: preamplifier electronic noise and the statistics of the collection of the charge due to the ion pairs formed. These effects are added in quadrature to give the resultant resolution.

The electronic noise is independent of energy and can be described as a fixed term due to thermal noise, inherent noise in transistors, etc., and a term that is proportional to the capacitance (C) of the detector. A typical modern preamplifier, operated with a field-effect transistor in the charge amplification loop at room temperature, will have full-width-at-half-maximum (FWHM) noise, $(FWHM)_N \approx (0.65 + .02 C(\text{pf})) \text{ keV}$.

The production of ion pairs in a Ge(Li) crystal is a correlated process and the usual Poisson statistics are modified via the "Fano factor"²³ to account for this. The formula for the intrinsic resolution, $FWHM_i$, is

$$(FWHM)_i = 2\sqrt{2En_2}\sqrt{F_F E},$$

where E is the energy of the photon,

ϵ is the average energy to form an ion pair, and

F is the Fano factor.

For Ge, $\epsilon = 2.96$ eV/ion pair. For high quality crystals, with a minimum of charge recombination and trapping at impurity sites, $F = 0.1$ and thus

$$(\text{FWHM})_1 = 0.0406 \sqrt{E(\text{keV})} \text{ keV}.$$

The dependence of the resolution on E and C is shown in Figure 7. From the figure, the relative importance of a low-noise preamplifier and low capacitance of the detector is diminished at several MeV by the statistics of the charge collection. This was acknowledged in the design of the first high-energy detector that was employed in this experiment. This detector was a long, narrow, true coaxial design (17.6 cc) and had a 50-pf capacitance. The resolution in the system was 6 keV at 6 MeV. This detector was damaged during the course of the experiment and a replacement was obtained which had a different geometry (14.3 cc) and a 13-pf capacitance. The latter detector had better low energy resolution but the high energy resolution was a comparable 6 keV at 6 MeV.

The mounting of the two crystals which were used in the three-crystal spectrometer will now be described. The first was a true coaxial diode 2 cm diameter by 7.6 cm long (17.6 cc volume) mounted in a long thin end-cap (see Figure 8(a)). The crystal was situated on a thin aluminum cold finger that was placed in thermal contact, but electrically isolated, from a tube containing liquid nitrogen by using a sapphire disc. Indium

gaskets were used between the sapphire-aluminum and Ge-Al surfaces to assure good thermal contact. Positive high voltage was applied to the cold finger and the signal was extracted with a contact touching the center of the coax. No heat shield (to protect the crystal surface from infrared radiation) was used. The γ -rays were incident along the axis of the crystal.

Halfway through the data collection phase of the experiment a small leak developed in the vacuum jacket of the 17.6-cc detector. The crystal was removed and the leak repaired, but the detector was permanently damaged.

A second detector was purchased with a special mounting and end-cap specified. This detector was a 14.3-cc coaxial diode, 31.5 mm diameter by 19.5 mm long with a closed-end drift (i.e., lithium is drifted from one end as well as the outside of the cylinder). The detector was mounted transversely so that the gammas were incident upon the side of the cylinder. The dimensions and orientation are shown in Figure 8(b). The electrical isolation, signal pickoff, and cold finger arrangement were similar to the first detector. In addition, a thin Al heat shield surrounded the crystal.

Both detectors were oriented such that they presented the greatest possible depth to the incident photons and the least amount of material to impede the escape of 511 keV photons out the sides.

In operation these detectors were sandwiched between two 127-mm diameter by 127-mm thick NaI (Tl) scintillators and enclosed in a combination bismuth and lead γ -ray shield. Shielding from scattered neutrons was provided by a 12.7-mm

thick 152-mm diameter disc of ^6LiD placed between the sample and the Ge(Li) detector (see Figure 9).

The detector peak efficiency was measured with calibrated γ -ray^{30,31} sources and thermal neutron capture γ -rays from natural chlorine and chromium.³²⁻³⁴ Since the effective interaction depth is a function of photon energy and since it is desirable to know the efficiency for all source to detector distances, the efficiency, $\epsilon(E_Y, R)$, was measured both as a function of source energy and distance and parameterized as follows:

$$\epsilon(E_Y, R) = \epsilon_0(E_Y) / (R + R_0(E_Y))^2$$

where $\epsilon_0(E_Y)$ is the "intrinsic" efficiency in mm^2 , R is the distance from source to end-cap, and R_0 the effective interaction depth measured from the end window. The results of the calibration are plotted in Figures 10 and 11 for the 17.6 and 14.3 cc detectors respectively.

The operation of the diode in the three-crystal coincidence mode reduces the efficiency for detection of the double-escape peak to 20% of the value of the diode alone due to the finite efficiency of the NaI detectors for photopeak detection of the annihilation radiation. The peak to total response ratio is improved from $\sim 1\%$ to $\sim 50\%$ using the triple coincidence method. The response function for monoenergetic photons was extracted by measuring the response to the 2250-keV $\text{H}(n, \gamma)\text{D}$ capture γ -ray, the 2615-keV ^{228}Th line, the 4430-keV line from the $^9\text{Be}(\alpha, n)^{12}\text{C}^*$ reaction from a PuBe source, and the 6141-keV ^{16}N line. Corrections were made for background and contributions from other lines in the spectra. The response functions for the 2615- and 6141-keV photons are shown in Figure 12.

B. Electronics

In order to measure the capture gamma spectra to the desired accuracy in neutron energy and γ -ray energy it is necessary to record the time of a capture event after the beam pulse to ~ 20 nsec accuracy and the energy deposited in the detector to $\sim 0.1\%$ accuracy.

The time interval was measured with a time digitizer (TD), which is a clock that converts the time between a start pulse (from the e^- beam burst) and a stop pulse (from the capture event) to a 36-bit computer word with a precision of $1/8$ nsec. The selected significant bits were transferred to a buffer and constituted the time interval portion of the event descriptor. The linear signal, which was proportional to the energy deposited in the detector by the capture event, was fed into an analog-to-digital converter (ADC) which converted the pulse height to a 12-bit word which was transferred to the event descriptor buffer.

To achieve the ultimate energy resolution capability of a Ge(Li) detector, the signal must be integrated for times sufficiently long to average out noise, effects of pile-up between pulses must be minimized, and there must be compensation for long-term drifts in amplifier gains and linear gate pedestals.

Normally the integration and pile-up criteria are met by using quasi-gaussian shaping with pole-zero cancellation in the main amplifier. The preamplifier output pulse is essentially a voltage step with a rise time (corresponding to the charge collection time in the Ge(Li) diode) of < 100 nsec and a decay time of 50 - 1000 μ sec. The main amplifier operates on this function with equal integration and differentiation times to

produce a quasi-gaussian shaped output pulse with a width approximately equal to those time constants. To average the noise adequately and thus approach the resolution capability of the detector, time constants on the order of $3 \mu\text{sec}$ are needed. The time for the pulse to return to baseline so that another pulse can be accepted is about five times as long. The dual requirements of fast return to baseline and adequate integration over the noise are in direct conflict with each other.

To resolve this conflict the following technique was used. The main amplifier was operated with $0.25 \mu\text{sec}$ shaping. This was short enough to allow return to baseline within a few μsec and yet long enough to collect sufficient charge information from the voltage step. The signal was then sent to a Tennelec (TC301) linear gate, operated in the integrating mode. After pile-up and associated coincidence criteria were met the gate was opened and the signal was integrated for $3 \mu\text{sec}$. After integration the signal-to-noise ratio (and hence the resolution) was restored.

Long-term gain stability was achieved by injecting pulses from a stable pulser with a temperature-controlled power supply into the test input of the preamplifier. This produced a peak in the high-energy portion of the spectra that a digital stabilizer maintained at a constant centroid by adjustments of the ADC gain. Similarly, zero intercept stability was achieved by injecting a low-level pulse into the differential input of the main amplifier and thus inserting a peak in the low-energy portion of the spectra. The digital stabilizer maintained the centroid of this peak at a constant value by adjustment of the zero intercept of the ADC.

Figure 13 shows a schematic block diagram of the electronics. Signals from the direct-coupled detector were charge amplified by the preamplifier, fed into an extrapolated zero timing circuit (XLET), and bridged over to a main amplifier (LA1). After shaping and amplification, the signal was fed to the integrating linear gate (LG1) which opened for $3 \mu\text{sec}$ after the appropriate coincidence and pile-up criteria had been met. The signal was then sent to linear-gate-stretcher (LG2) which provided a suitably shaped pulse for analysis by the ADC.

The output of the timing unit was fed through an OR circuit to a pile-up-rejector (PUR) which gave an output signal only if there had not been a preceding pulse within $3.1 \mu\text{sec}$. This output was fed through a delay-gate-generator* (DG) to an overlap coincidence (C2).

The Ge(Li) timing signal was also sent to a coincidence unit where the γ -flash was vetoed. This signal was then sent through a triple coincidence unit (in the case of three-crystal experiments) or passed directly to C1 where signals were derived to trigger LG1, LG2, and provide a stop signal for the time digitizer.

The pulser used for gain stabilization produced pulses for injection into the NaI circuitry as well as the Ge(Li) preamplifier so that the coincidence criteria could be satisfied for the pulser. The pulser could be triggered externally as well as from

*The delay-gate-generator is a unit which accepts either negative (NIM level) or positive (TTL level) pulses and generates a pulse of adjustable amplitude (-20 to $+20$ V), delay ($.1$ - $10 \mu\text{sec}$), and width (20 nsec to $10 \mu\text{sec}$). It is useful for interfacing devices with conflicting input-output requirements.

an internal variable frequency oscillator. The outputs could be delayed for times as long as several milliseconds after the trigger. By using a linac-generated pulse as a trigger, the stabilization pulses could be injected in a time interval where there was no conflict with the data. The frequency divider circuit was constructed so that the pulser was triggered for only one of every N beam pulses, where N was typically 33.

The low-level stabilization pulser (LLP) was injected at random times, at a rate of $\sim 10/\text{sec}$, into the differential input of the main amplifier (LA1). Since this does not trigger either the XLET unit or the NaI circuitry, the trigger pulse from the LLP was used to form an OR with the XLET, and another OR with the triple coincidence output, to allow the pulse to be routed through the electronics, subject to pile-up rejection.

The start pulse for the TD was derived from the linac beam target pulse. The delays of the start, stop and linear signals were adjusted to be coincident for the γ -flash. Thus the lowest descriptor produced by the TD corresponded to the arrival of the γ -flash at the detector. This information along with the flight path and the time/channel of the TD completed the calibration of time-of-flight vs channel number.

The electronics for the NaI(Tl) detectors and the triple coincidence circuit are shown in Figure 14. To optimize performance in the presence of large signals due to the γ -flash the phototube base was modified to put negative high voltage on the cathode and DC-couple the anode output signal. An electrostatic shield at cathode potential surrounded the phototube to suppress noise. The divider string was "stiffened" by reducing the total

divider resistance from the recommended 6.12 $M\Omega$ to 1.2 $M\Omega$ to aid recovery from large signals.

The anode signals were fed into the negative inputs of linear amplifiers MA1 and MA2. The HLP pulser signals were mixed in at this point through positive inputs. Shaping time constants of 0.05 μsec integration and 0.1 μsec differentiation were used. One output of each amplifier was fed to a low-level leading edge discriminator (TPO) while a second output went to a single-channel analyzer (SCA). The TPO units provided a timing signal with which to strobe the outputs of the SCA's which had "windows" set on the 511-keV positron annihilation line. These outputs, along with the Ge(Li) timing signal, were sent to a triple coincidence unit. The resolving time was set at 40 nsec to accept events on the wings of the time-resolution curves. The FWHM timing response was < 15 nsec.

The delay amplifier and linear gate (LG) were used to monitor the output during setup of the timing and energy "windows". A low-level positron-emitting source, ^{22}Na , was used for calibration. The positron annihilation, in coincidence with 1275-keV photons, provided a convenient source of triple coincidences when the source was placed next to the Ge(Li) diode between the NaI scintillators.

C. Overload Recovery

In order to collect high resolution γ -ray spectral data in the neutron energy range 2 eV to 10^5 eV it is necessary for the Ge(Li) detector system to be functional in the time interval 3 to 700 μ sec after the linac beam burst at the flight path (13.4 m) of this experiment. Each beam burst is accompanied by a γ -flash caused by the electron beam stopping in the neutron-producing target. For Ge(Li) detectors of greater than 10-cc volume and samples of greater than 80 g of Ta, more than 100 MeV can be deposited in the detector by each γ -flash.

A typical low-noise charge sensitive preamplifier used in high resolution spectroscopy produces a voltage step proportional to the charge collected for each event with the ~ 1 msec decay time of the step determined by the charge feedback loop. The gain is such that a charge proportional to ~ 50 MeV will produce saturation. Thus a γ -flash depositing > 100 MeV will paralyze the preamplifier for times > 1 msec rendering the system inoperative in the time interval of interest.

It is possible to reduce the amplitude of the γ -flash by use of moderators with shadow bars and by putting high-Z filters in the beam, but these solutions are costly in the reduction of the neutron flux. It is not possible to reduce the gain or shorten the time constant of the charge feedback loop without adversely affecting the resolution capability of the preamplifier. It is therefore useful to pursue methods of enabling the preamplifier to recover in short times in the presence of large overloads.

Radeka³⁵ developed a method for handling this situation. (See the circuit shown on Figure 15.) Basically a current source (of opposite polarity of the overload) switched on and off by a field-effect transistor (FET) is connected to the input of the preamplifier. The switching is controlled by a Schmidt trigger at the output of the charge loop. Normally the FET is nonconductive and does not affect the operation of the preamplifier. When the Schmidt trigger senses an overload the FET is switched on and an opposing charge is injected into the input from the current source through the FET. When the output of the charge loop returns to zero volts the switch is turned off and the preamplifier is ready to accept another event.

This circuit was used in the experiment but presented some difficulties for the system for times less than 20 μsec . First the overload from the γ -flash was collected in times less than 100 nsec. This drove the preamplifier into saturation before the Schmidt trigger could respond. Consequently the main amplifier had a square pulse of $\sim 10\times$ saturation level to contend with at the time of the γ -flash. Even though the preamplifier had recovered about 1 μsec after the flash, the main amplifier took about 20 μsec to recover to noise level.

In our application the time of the γ -flash could be determined from the linac pre-injector pulse which precedes the e^- burst by about 3 μsec . The width and approximate amplitude of the γ -flash were known from the electron beam parameters. Therefore an alternative method was developed. (See Figure 16.) A voltage divider was constructed to bias off the switching FET. During the time of the γ -flash a pulse was applied at point Q

which was adjusted in amplitude, width and shape so as to optimally cancel the overload.

If every γ -flash had been identical it would have been possible to achieve almost perfect cancellation by this method. However, two effects prevented this. First, each γ -flash consisted of the sum of several hundred individual photons. The statistical variation from this source gave a several percent uncertainty in the prediction of an individual amplitude. Second, the linac itself had variations of the order of 1 to 2% in the amplitude of each beam burst. Consequently, while it was possible to achieve excellent cancellation in the first 90% of the burst, a family of voltage steps corresponding to this variation was introduced at the end of the pulse. These steps were of sufficiently small amplitude that the main amplifier was not usually saturated. With the use of short (.25 μ sec) time constants in the main amplifier, recovery was complete within 5 to 6 μ sec after the burst.

III. General Data Analysis

This section contains a general description of the computational procedures employed in the programs used for the analysis of the data. A more complete description of the programs is given in Appendix I.

The spectral data for each experimental run were accumulated in a matrix consisting of 624 time-of-flight channels by 4088 pulse height channels which was stored on-line on a three-million 18-bit word drum. These data were subsequently stored on magnetic tape for further processing with a CDC-6600 computer having a 10^5 , 60-bit word memory, operated in a time-sharing mode. Some of the input/output (I/O) devices associated with this system are teletypes, printers, magnetic tapes, large fast-access disk storage, CRT graphics, microfiche, and off-line Calcomp plotters. A versatile software system is available to facilitate text editing, compilation of fortran programs, assembly of libraries of commonly used routines, and loading of executable programs. Utility programs are available for manipulation of disk files and transfer of files to and from magnetic tape and to output devices.

This type of operating system is optimized for small interactive programs rather than larger production codes. For this reason, and since it is desirable to examine the results of the data analysis at intermediate stages, it was decided to develop a collection of small interactive codes, each of which would perform a rather limited phase of the data analysis, with communication between codes via disk files, rather than attempt to analyze a set of data from raw form, stored on magnetic tape,

to the finished form in one step. A library of commonly-used subroutines was developed to facilitate programming of codes for each specific analysis step. These routines included programs to facilitate reading and writing of disk files of specific forms, and programs to make the input as format free as possible.

The first step in the analysis was the conversion of data from raw form to standard disk file formats. This was done with a set of programs prefixed DCON-. The output disk files had two binary forms (1-D or 2-D) depending on whether the data was one- or two-dimensional. The first seven (or eight) words of either file contained alphanumeric identification and the dimensional size of the data. The 1-D files also contained a statistical error associated with the count of each channel.

The second set of programs is prefixed DTLK-. Two of these programs operate on 2-D files to compress the counts within a selected set of descriptors into a 1-D file. For example, selected pulse heights can be added together to produce a one-dimensional time-of-flight spectrum or a particular neutron resonance can be extracted to give a γ -ray spectrum for that resonance, or several between-resonance regions can be summed to form an off-resonance γ -ray spectrum. The first code takes instructions interactively from teletype; the second from a format-free card file. Printing and plotting features are available in both versions.

There are two corresponding 1-D programs which operate on files with 1-D format. One took its instructions from teletype, the other from card files. These codes allow addition and subtraction of 1-D files, editing, compression, repetitive

three-channel binomial smoothing, and creation of 1-D output disk files as well as printing and plotting of the data.

From this point the data analysis can take one of two branches depending upon whether the 1-D data is a function of time-of-flight or pulse height. The time-of-flight branch will be considered first.

A code, TOF1, operates on 1-D files, converting the raw counts vs channel to a deadtime-corrected count rate, with the associated errors, as a function of neutron energy. A disk file with a third binary format (TOFFILE) containing this data is created. Plots and printouts of the data are generated.

The next code (TOF2) is used essentially for producing the final neutron cross-sections and ratios of cross sections by performing the operation

$$R(E) = N \frac{R_1(E) - B_1(E)}{R_2(E) - B_2(E)} E^\eta S(E) \quad (7)$$

where N and η are arbitrary constants. The term $E^\eta S(E)$ can be used to parameterize the cross section used in the flux monitor. For example, if the cross section predominantly follows a $1/v_n$ behavior, the cross section can be parameterized as $\sigma = E^{-1/2} S(E)$. The arrays subscripted 1 and 2 usually refer to the cross-section rates and the flux rates, R , (and backgrounds, B) respectively. The points $R(E_i)$ are computed at the energy intervals, E_i , associated with R_1 . The other arrays are determined at E_i by linear interpolation. The arrays R_1 , R_2 , B_1 , B_2 have error arrays associated with them. Options are available for converting neutron transmissions to total cross sections, and for skipping portions of the operations of eq. (7). An output file of the

form, TOFFILE, is created, and thus the output of TOF2 can be fed back into itself to be able to perform eq. (7) repetitively. Plots and listings of the data are available.

The last two codes of this series of codes are prefixed PNA-. The first accepts as input 1-D disk files or ASCII card image files; the second, either TOFFILES or ASCII card images. They perform editing, averaging, printing and plotting of the data as well as creating an optional output file of TOFFILE form. With these codes, Calcomp plots may be generated with the scales and ranges of the data chosen so as to produce high-quality plots.

Analysis of the γ -ray spectra for peak positions and areas of the γ -ray lines was done with a series of programs prefixed with PEAKS-. In view of the large volume of data it was decided to automate the procedure as much as possible. The first step in this procedure was determination of peak regions in the data. The following algorithm was developed. The peak-finding subroutine was given the parameters $\bar{w}$ and SD , where $\bar{w}$ is the average peak width and SD is the number of standard deviations of the channel counts from a "smoothed background" used to determine the presence of a peak. The "smoothed background" was determined by performing a running average, $\bar{C}_i$, at each channel, i , over $1.5\bar{w}$ channels on each side of channel i . If $(C_i - \bar{C}_i) \geq SD \cdot \Delta C_i$, a flag was set. C_i and ΔC_i are the contents and standard deviation of the i th channel. The procedure was repeated, using the previously computed $\bar{C}$ in the computation of the average if the flag was set, until the array of flags did not change. This procedure is illustrated in Figure 17. The upper graph shows the data and the results of the running average for the first, second, third

and last cycle. The lower graph shows the development of the flagged regions as the running average is lowered toward the "smoothed background". The final array of flags is examined to discard erratic regions (i.e., a flag due to a single high channel) and to merge peaks that are within $\bar{w}$ of each other. From these flags, arrays of channels that define the beginning and ending channels for each peak region are obtained.

The next step in the analysis was fitting a function that described the detector response to the peak regions. In general the function is nonlinear. Consequently it was necessary to use a weighted nonlinear least squares fitting procedure to extract the parameters of the assumed functional relationship discussed below. A subroutine, SEARCH, was developed, based on the method of Marquardt³⁶ as described by Bevington³⁷, which was used in all of the fitting procedures. This method is discussed in detail in Appendix I.

The function which describes the detector response to a single peak is shown schematically in Figure 18. It was experimentally determined to be

$$f = f_b + f_f + f_p, \quad (8)$$

where f_b is a quadratic background,

$$f_b = a + bx + cx^2, \quad (9)$$

where x is the channel number. The function, f_f , describes the step that is found between the low- and high-energy sides of a peak caused by small angle scattering of the photon in the sample and detector window. This response was assumed to be a convolu-

tion of a step function with a gaussian of full-width-half-maximum, w . This convolution is not suitable for rapid computation. However, it resembles the function that describes the distribution of energies near the surface of a Fermi gas. Therefore, it was approximated by

$$f_f(x) = Af_{fm}(E_{Y0})(dx/dE)/(1 + e^{4(x-x_0)/w}), \quad (10)$$

where E_{Y0} is the energy of the peak and A and x_0 are its area and centroid. The quantity f_{fm} , the fraction of the peak area/unit energy, was determined experimentally by fits to isolated peaks. Its functional dependence on E_{Y0} was determined and subsequently fixed.

For a gaussian response, the peak function is given by

$$f_p = 2\sqrt{\frac{\ln 2}{\pi}} A/w e^{-4\ln 2((x-x_0)/w)^2}. \quad (11)$$

Some of the data exhibited low-energy tailing. It was found that in this case the response could be described by replacing a portion of the low energy side of the peak by $k A e^{s(x-x_0)}$ where k and s are experimentally determined constants. This function was joined to the gaussian so as to preserve continuity of the function.

The width, w , is also energy dependent with the functional form

$$w = \sqrt{a_w^2 + b_w x}. \quad (12)$$

The coefficients a_w and b_w were determined by fitting a single peak to each of the peak regions and allowing w to be a free parameter. The functional form (12) was fit to this set of widths. Because some of the peaks had insufficient statistics,

and some were multiplets, those points with large errors were rejected initially. The remaining data were fit with eq. (12) and the points which were more than two standard deviations from the fit were excluded until a consistent set was determined. The parameters, a_w and b_w , could also be fed as input into the codes.

Once the functional relationships for f_{fm} and w were determined, the peak regions were fit with the function

$$f = f_b + \sum_{i=1}^M (f_{fi} + f_{pi}), \quad (13)$$

where M is the number of peaks in the region. M was set initially to 1, the fit made and the residuals examined to see if more peaks were needed. If so, M was incremented and peaks were inserted where the residuals were sufficiently positive. The procedure was repeated until no more peaks were needed to fit the data. A maximum of ten peaks and 100 data points were allowed per region. A sample fit is shown in Figure 19.

A second version of this peak fitting code, with card file input, was used in the production mode. The functional relationships were assumed to be known and only relation (13) was fit to the data. This procedure was about 95% effective in extraction of all peaks with their intensities and centroids. For those regions where the fit was not satisfactory a third code allowed input of a fixed number of peaks in a given region. The output of this code could be merged with the output of the previous one to give a file listing the parameters of all the peaks in a set of data.

Because of the Porter-Thomas³⁸ fluctuations in the partial radiation widths, many transitions may not be observable in a given neutron resonance. To find a consistent set of transition intensities for all observable radiation widths, the results for each individual neutron resonance were examined and a list of peak positions for all observable transitions compiled.

The data for all resolved neutron resonances were then refit with the peak positions taken from the list and fixed. Since the peak positions were not allowed to vary, the fitting function was now linear in the parameters and fitting was accomplished in one pass for each peak region. The result of this analysis was a list of all transitions for a given neutron resonance with an error assigned to the intensity.

The final stage of analysis involves conversion of channel centroids to absolute energies and conversion of counts in a peak to intensities expressed as number of gammas per 1000 captures.

Because of nonlinearities in the response of the amplifiers, linear-gates and the ADC, the relationship between energy and channel number, x , cannot be described adequately by

$$E_{\gamma} = A + Bx. \quad (14)$$

It was found empirically that the function

$$E_{\gamma}(x) = a e^{-bx} + \sum_{i=1}^N c_i x^{i-1} \quad (15)$$

describes the relationship between E_{γ} and x adequately with $N = 4$. The energy calibration was done by a least-squares fit of eq. (15) to peak positions from known γ -ray energies from

^{226}Ra , ^{228}Th , and ^{60}Co sources and from chlorine thermal neutron capture lines. A typical nonlinearity (i.e., the deviation in channels from a least-squares fit of a straight line to the data) is shown in Figure 20.

The code SPEAKS converted the list of channel centroids and peak areas from a particular γ -ray spectrum to the energy of the transitions, excitation energies of the final states, and photons per 1000 captures by applying a normalization constant, detector efficiency, energy calibration, and Q value to the data.

IV. Results

A. Resolved Primary Transitions

In this section the analysis and results of the data for the resolved primary spectra will be presented. The data were sorted into two groups. The first group consisted of a set of 19 resolved neutron resonances of known spin and parity. The second set consisted of spectra summed over large bins of neutron energy in the range 20-3000 eV. From the first set, information was obtained on spins and parities of the final states in ^{182}Ta , as well as the E1 strength function and the statistical distribution of partial radiation widths for E1 transitions. From the second set, information was obtained on the neutron energy dependence of the averaged primary intensities and the strength function.

These data were taken with the 17.6 cc Ge(Li) detector in the three-crystal spectrometer with the sample at 13.47 m from the neutron target. The sample was a 50- x 100-mm sheet of Ta, 0.965 mm thick. The electron beam parameters were: 100 MeV, 720 Hz, 100 nsec pulse width, with an average current of 100 μA . The total running time was 75.4 hours. No shadow bar was required for this relatively low neutron energy run. The counting rate as a function of neutron energy is shown in Figure 3. Sample γ -ray spectra for the 4.28-eV neutron resonance and for the neutron energy intervals from 20 to 100 and 100 to 200 eV are shown in Figure 21.

As a consequence of the Porter-Thomas fluctuations in the partial radiation widths, there is a high probability that any given transition in a given neutron resonance will have such a

small width as to be unobservable. Therefore the density of observable peaks should be smaller for isolated resonances than for spectra summed over many neutron resonances. This can be seen by comparing the spectra for the 4.28-eV resonance in Figure 21 with the summed spectra. Consequently, if we analyze spectra from isolated resonances, peaks can be resolved to a much higher excitation energy. If the sample of isolated resonances is large enough, the probability of missing E1 transitions will be small. Table I shows the resonances analyzed individually. All were adequately resolved; published values of the spins and parities were used in this analysis.

The γ -ray peak positions and areas were extracted using the method described in the previous section. Because of statistical fluctuations causing spurious peaks to be injected into the fits by the peak-fitting routine, a three-channel binomial smoothing was first applied to the data. (The contents of channel C_i were replaced by $0.25 C_{i-1} + 0.5 C_i + 0.25 C_{i+1}$.) This reduced the statistical fluctuations while broadening the resolution only slightly. It can be shown³⁷ that if the data are represented by a gaussian peak with width σ ,

$$g(x) \sim e^{-(x-x_0)^2/2\sigma^2} \quad (16)$$

then the width, σ_s , after three-channel smoothing, is

$$\sigma_s^2 = \sigma^2 + \frac{1}{2}. \quad (17)$$

In terms of the FWHM, w , instead of σ , eq. (16) becomes

$$w_s^2 = w^2 + 4 \ln 2. \quad (18)$$

For these data, this implied only a 10% broadening of the peaks.

The areas of the extracted peaks were converted to intensities via the following procedure. It was assumed that for a heavy nucleus such as Ta the capture spectrum is sufficiently complex that the total number of counts obtained by integration over a sufficiently large span of γ -ray energy should be proportional to the number of neutron capture events occurring in the sample. For each neutron resonance, i , the number T_i was extracted, where T_i was the sum of all counts in the channels which corresponded to the γ -ray energy range from 2.4 to 6.1 MeV. T_i was corrected for background and continuum events under the resonance. The intensity, I_{if} , for the transition from initial state, i , to final state, f , is given by

$$I_{if} = N \frac{A_{if}}{T_i \epsilon(E_{\gamma if})} \quad (19)$$

Here, A_{if} is the area of the peak at energy $E_{\gamma if}$. $\epsilon(E_{\gamma if})$ is the detector efficiency shown in Figure 10. N is a constant chosen to normalize the sum of the intensities of the 6063-, 5965-, 5889-, and 5770-keV transitions of the 4.28 eV neutron resonance to the values of reference (15). These values were determined by measuring the intensity of the ground-state transition in ^{181}Ta at thermal neutron energy relative to the intensities of the 5661- and 6877-keV transitions in cobalt. The result for the ground-state transition intensity is $I_{G.S.} = 6.2 \pm 1.0$ photons/1000 captures. From the uncertainties in the measured intensities and the uncertainties quoted in reference (15), $N = 0.102 \pm 0.005$ was used to normalize the data to photons/1000 captures.

The energy calibration was established relative to natural chlorine thermal neutron capture lines,³²⁻³⁴ via the technique described in the previous section. Assuming the 6062.6-keV transition in the ^{181}Ta neutron capture data to be the transition to the ground state, the Q value for the $^{181}\text{Ta}(n,\gamma)$ reaction was determined by the relation

$$Q = E_{\gamma} + \frac{1}{2} \frac{E_{\gamma}^2}{M_T c^2},$$

where $M_T c^2$ is the rest mass of ^{182}Ta . This yielded $Q = 6062.7 \pm 0.5$ keV which is in agreement with the results of Wasson *et al.*¹⁵ at 6063.0 ± 0.6 and Helmer *et al.*¹⁶ at 6062.9 ± 0.5 .

Table II lists the excitation energies of all levels which were observed here below an excitation of 1790 keV in ^{182}Ta . Comparison with the level schemes of references (15,16) is also given. All transitions, with the exception of those labeled with "*" or "U" under "present results", were observed in our set of 19 resonances. The levels labeled "U" were unobserved and those with "*" were seen only in the averaged data. The uncertainties in the excitation energies were determined from the standard deviation in the centroid of the peaks, as determined by the least-squares fitting program, or set to 0.5 keV, whichever was larger. A total of 113 transitions to states below 1780 keV excitation was observed in the resolved resonance spectra and the spectra averaged over neutron energy.

Theoretically,^{1,3-5,7} the average transition rate or width for a transition of multipolarity, L, from initial state $J_i^{\pi_i}$ to final state $J_f^{\pi_f}$ is given by

$$\bar{\Gamma}_{XLif} \sim D_{J_i}^{\pi_i} E_{Yif}^{2L+1},$$

where X is either E (electric) or M (magnetic) and $D_{J_i}^{\pi_i}$ is the level spacing of initial states of spin and parity $J_i^{\pi_i}$. For γ -ray energies around 6 MeV, theoretical estimates¹⁻⁵ are that M1 rates are $\sim 1/10$ the E1 rates and higher multipolarities are orders of magnitude lower still for this region in the periodic table. The selection rules for transitions from a state $J_i^{\pi_i}$ to state $J_f^{\pi_f}$ are

$$|\vec{J}_i - \vec{J}_f| \leq L \quad (20)$$

and

$$\left\{ \begin{array}{l} \pi_f = (-1)^L \pi_i \text{ for EL} \\ \pi_f = (-1)^{L+1} \pi_i \text{ for ML} \end{array} \right\} \quad (21)$$

It is therefore reasonable to define a partial strength function, S_{if} , for dipole radiation as

$$S_{if} = \frac{I_{if} \Gamma_\gamma}{D_{J_i} E_{Yif}^3}, \quad (22)$$

where Γ_γ is the total radiative width of the compound state. Then, by averaging S_{if} over the 3^+ and 4^+ initial states respectively, there should occur three groups of average S_{if} , depending on whether the transition can proceed by E1, M1, or only higher order multipole transitions. Thus if $\bar{S}(3^+ \rightarrow 2^-, 3^-, 4^-) = \bar{S}(4^+ \rightarrow 3^-, 4^-, 5^-) = 1$, then $\bar{S}(3^+ \rightarrow 2^+, 3^+, 4^+) = \bar{S}(4^+ \rightarrow 3^+, 4^+, 5^+) \sim 0.1$, and $\bar{S}(3^+ \rightarrow 5^\pm) = \bar{S}(4^+ \rightarrow 2^\pm) \sim 0.0$. Therefore determinations as to whether the final state spin and parity is $2^\pm$, $(3,4)^\pm$, or $5^\pm$ can be made.

For $^{181}\text{Ta} + n$ at low neutron energies, only 3^+ and 4^+ initial states in ^{182}Ta can be populated from the $(7/2)^+$ ground state of ^{181}Ta by s-wave neutrons. The experimentally measured level spacing for 3^+ and 4^+ states is 4.4 ± 0.3 eV.³⁹ If it is assumed that the level density, ρ_J , in ^{182}Ta for states of spin J can be expressed as

$$\rho_J = (2J+1)\rho_0(E), \quad (23)$$

and

$$D_J = 1/\rho_J,$$

then $D_3 = 10.1$ eV and $D_4 = 7.82$ eV where D_3 and D_4 are the level spacings for $J = 3$ and $J = 4$ states respectively. In eq. (23) $\rho_0(E)$ describes the excitation energy dependence of the level density. The experimentally determined Γ_γ for neutron resonances in ^{182}Ta is (55 ± 2) meV.³⁹ Therefore S_{if} in eq. (22) can be expressed as

$$S_{3f} = \frac{5.45 \times 10^{-6}}{E_{\gamma if}^3} I_{3f} \text{ MeV}^{-3} \quad (24a)$$

and

$$S_{4f} = \frac{7.05 \times 10^{-6}}{E_{\gamma if}^3} I_{4f} \text{ MeV}^{-3} \quad (24b)$$

where the intensities are expressed in photons/1000 captures and $E_{\gamma if}$ is in MeV.

The set of intensities, I_{if} , was extracted from the resonance data by fitting to each of the 19 resonances all the gamma lines found in any of the 19 resonances listed in Table I plus lines found in the background. Equations (24) were applied to this set of intensities and the spins and parities extracted as

discussed above. The results are compared in Table II with results of Wasson et al.,¹⁵ which were obtained from γ -ray spectra for eight resolved neutron resonances using a single crystal Ge(Li) spectrometer at the Brookhaven fast chopper, and the results of Helmer et al.¹⁶ who studied the level structure of ^{182}Ta using the decay of ^{182}Hf , $^{182\text{m}}\text{Ta}$, thermal neutron capture by ^{181}Ta and 2-keV (Scandium filter) neutron capture by ^{181}Ta with single crystal Ge(Li) spectrometers. The latter have included the $^{181}\text{Ta}(d,p)$ ^{182}Ta results of reference (18) along with a private communication from J. R. Erskine in their proposed level scheme for ^{182}Ta .

The present results are in reasonably good agreement with the other two experiments in the region of overlap. A weak transition to a state at 90.2 keV was seen in the present resolved resonance data that was not seen by either of the previous investigators. The intensities for this line were at the threshold of observability except in the 4.28- and 25.9-eV 4^+ resonances. If the J^π of this state is 3^+ or 4^+ , a strong 90.2 E1 transition to the ground state would occur which is not consistent with the weak 90.1-keV transition observed in the low γ -ray energy thermal neutron capture data of Helmer et al.¹⁶ Therefore, the state probably has $J^\pi = 5^+$.

Other previously unreported states below 1250 keV, which were observed in the resonance data, occur at 365.5, 1021.6, and 1203.1 keV. These levels are all positive parity and the transitions populating them from the capture states are consequently weak. All of these transitions are within 8 keV of strong E1 transitions and could easily be missed in averaged

spectral data with a spectrometer having less than excellent resolution, or lacking the clean response of a three-crystal spectrometer. Levels previously unreported in this excitation range were also observed at 245.8, 458.2, 662.8, 791.0, and 830.5 keV in the average spectra. Helmer et al.¹⁶ report levels with E, J^π of 331.3 keV, 5^+ ; 402.65 keV, 2^+ ; 423.5 keV, $(2^+, 5^+{?})$; 474.7 keV, 3^+ ; 586.6 keV, $(2^+, 5^+{?})$; 866.3 keV, $(2, 5^-)$; and 935.8 keV, $((2-5)^+)$ from transitions in the 2-keV average neutron capture spectra that were not seen in the present results. (The "?" following the J^π means that Helmer et al. consider the existence of these levels in doubt.) With the exception of the 866.3-keV level, these are all M1 transitions. All but the one to the 474.7-keV level have $J_f = 2^+$ or 5^+ and thus have only half the probability of being observed as a 3^+ or 4^+ state.

Wasson et al.¹⁵ observed most of the allowable dipole transitions below 1300-keV excitation seen in this experiment. They do report a level at 1054.2 keV which is not observed in either the work of Helmer et al.¹⁶ or the present work.

Above 1330-keV excitation, the resolved resonance technique, combined with the simple response of the three-crystal spectrometer and the excellent resolution of the detector, allowed transitions to be resolved to 1780 keV. Forty-one previously unreported levels are observed in this region.

Wasson et al. quote uncertainties ranging from 0.6 to 1.5 keV in the excitation energies and these uncertainties are not listed in the Table. In general the agreement in excitation energies between Helmer et al.¹⁶ and the present work is excellent.

The spin and parity assignments have been determined by Helmer et al. for the states at 98.2, 114.6, and 270.1 keV by studying the β -decay of ^{182}Hf to the 270.1 keV state and by measuring the subsequent γ -cascade with the branching ratios from this state. The assignments for the 519.7-, 334.8-, 163.3-, and 16.9-keV states were made by observing the cascade, branching ratios, and electron conversion spectra for the decay of the 16-min half-life 10^- isomer of ^{182m}Ta at 519.7 keV. They attempted to extract further information on spins and parities of low-lying states by fitting the relative intensities of low energy transitions from thermal neutron capture to theoretical predictions. For final states with spins and parities in the range $2^{\pm}$ to $5^{\pm}$, they examined the intensities of primary transitions from the capture of an 800-eV wide beam of 2-keV neutrons and, by assuming an E^5 γ -ray energy dependence for these intensities, extracted the relative strength function. By examining the relative strengths, the final state spins and parities could be determined to be $(3,4)^-$, $(2,5)^-$, $(3,4)^+$, or $(2,5)^+$. Some additional information came from the strengths of the $^{181}\text{Ta}(d,p)^{182}\text{Ta}$ reaction.¹⁸ They attempted to consolidate this information into a self-consistent level scheme using a rotational model with Coriolis-coupling based on excitations of the deformed proton and neutron orbitals.

Up to an excitation energy of 668 keV there is excellent agreement between the present spin and parity assignments and those of Helmer et al. The states at 270.1 and 659.2 keV were assigned $J^{\pi} = 2^-$ by Helmer et al. However, we observed a definite strength for transitions from 4^+ resonances consistent

with M1 strength, while the strength from the 3^+ resonances was consistent with E1 strength. For the 659.2-keV state, an adjacent level of probable positive parity at 662.8 keV was observed in the average spectra. This state was not included in the fit of the resonance spectra and could explain the finite strength from the 4^+ resonances. Possibly there is also an unobserved positive parity level near 270-keV excitation.

Above 670 keV the agreement of spin and parity assignments between the present work and Helmer *et al.* is not as good. As excitation energy increases, the difficulty of making plausible assignments on the basis of nuclear models becomes increasingly difficult. Furthermore, above 840-keV excitation, they rely entirely on their 2-keV capture data to extract spins and parities. Since the Porter-Thomas fluctuations in their finite sample of capture states allow some overlap between sets of intensities for various combinations of final spin states, this disagreement is not unexpected.

To determine the distribution of reduced partial widths for E1 transitions, a set of 1240 transitions was selected from the 19 resonances in Table I. Possible doublets were rejected as were transitions to final states where the J^π assignments were in doubt. Since the raw partial widths $\Gamma_{J_i J_f}(E_{\gamma if})$ are functions of both γ -ray energy and the density of the initial states, the reduced partial widths were used. They are defined as the partial strength functions, S_{if} , in eq. (24).

The distribution of partial widths is expected to follow a chisquared distribution with ν degrees of freedom.^{1,2,4,8,38} This distribution, $p(s,\rho)$, is given by

$$p(s, \rho) = \frac{(\rho s)^{\rho-1}}{\Gamma(\rho)} e^{-\rho s} \quad (25)$$

where $s = s_{if}/\bar{s}$, $\rho = v/2$, $\Gamma(\rho)$ is the gamma function,⁴⁰ and $\bar{s}$ is the average of all s_{if} .

The simplest method of analysis for extracting v is to compute $\bar{s}$ and at maximum likelihood, find v by setting to zero the logarithmic derivative with respect to v of the likelihood function,⁸ (i.e., $\frac{\partial}{\partial v} L(v, \bar{s}) = 0$). The likelihood function is defined as

$$L(v) = \prod_{i=1}^N P(s_i, \rho), \quad (26)$$

where N is the total number of transitions. The result of this operation is

$$\frac{1}{N} \sum_{i=1}^N \ln s_i - \ln \bar{s} = \psi\left(\frac{v}{2}\right) - \ln\left(\frac{v}{2}\right), \quad (27)$$

where $\psi\left(\frac{v}{2}\right)$ is the digamma function.⁴⁰ Since the left-hand side is a function of the data only, and the right-hand side can be computed from tables of mathematical functions, a solution for v can be easily obtained. Using this method our result was $v = 1.7$. However, a fit of eq. (25), for this v , to the distribution of strengths was not satisfactory in the region $s > 1$, where the experimental error bars were smallest and thus the data most reliable.

Another method was tried which was based on that of Coceva et al.⁹ To account for the finite uncertainties of the sample, the data, with errors, were transformed to a data set s_{aj} , s_{bj} where s_a is the lower limit of the data point, and s_b the upper limit. The likelihood function $L(\bar{s}, v)$ was then defined as,

$$L(\bar{S}, v) = \prod_{j=1}^N \int_{s_{aj}}^{s_{bj}} p(\bar{S}, \rho) ds. \quad (28)$$

By forming the logarithmic derivative with respect to $\bar{S}$, a transcendental equation is derived,

$$\sum_{j=1}^N \beta_j = 0 \quad (29)$$

where if $a_j = v s_{aj} / \bar{S}$ and $b_j = v s_{bj} / \bar{S}$, then

$$\beta_j = 2 \frac{b_j^{(v/2)} e^{-(b_j/2)} - a_j^{(v/2)} e^{-(a_j/2)}}{\int_{a_j}^{b_j} t^{(v/2-1)} e^{-(t/2)} dt}. \quad (30)$$

Eq. (29) was solved by computer for successive values of v and the logarithm of the likelihood function (eq. (28)) calculated to find the most likely $\bar{S}, v$. The results were a value of $\bar{S}$ which was $\sim 10\%$ smaller than the simple average and a value of $v = 1.65$, which again did not fit well the data region $s > 1$.

A third fitting method was tried which followed that of Price et al.,¹⁰ which is essentially identical to the first method except that a truncation of the data was employed. The point of truncation was determined by the following method. The set of reduced errors, ϵ_j , was formed where

$$\epsilon_j = \Delta S_j / \bar{S}, \quad (31)$$

and $\bar{S}$ is the simple average of all S_j . Both the mean and median of the set of ϵ_j were computed. The point of truncation, α , was taken to be the lesser of the mean or median; all points with $S_j < \alpha \bar{S}$ were replaced with $0.5 \alpha \bar{S}$ and the average recomputed. The recomputed average tended to increase about 10% over the

original. The method of eq. (27) was applied to extract a $v = 1.9$ from the set of 1240 data points. Again the fit to the distribution for $s > 1$ was unsatisfactory.

The final method tried was that of Perkins.⁴¹ He defines a truncated chisquared distribution

$$P(s, \rho, \alpha) = \frac{F(\rho, \alpha)}{\Gamma(\rho)} (\rho s)^{\rho-1} \rho e^{-\rho s}, \quad \alpha \leq s \leq \infty \quad (32)$$

where α is the point of truncation and

$$F(\rho, \alpha) = \frac{1}{1 - \int_0^\alpha p(x, \rho) dx} = \frac{1}{1 - I(\rho, \alpha)}. \quad (33)$$

The quantity $p(x, \rho)$ is defined in eq. (25). $I(\rho, \alpha)$ can be redefined in terms of the incomplete gamma function⁴⁰ $\gamma(\rho, w)$ where

$$\gamma(\rho, w) = \frac{1}{\Gamma(\rho)} \int_0^w y^{\rho-1} e^{-y} dy, \quad (34)$$

and thus

$$I(\rho, \alpha) = \frac{\gamma(\rho, \rho\alpha)}{\Gamma(\rho)}. \quad (35)$$

Forming the likelihood function,

$$L(\rho, \alpha) = \prod_{i=1}^N P(s_i, \rho, \alpha)$$

and setting the logarithmic derivative to zero to find the maximum likelihood gives

$$\sum_{j=1}^N \left\{ \left[\frac{d}{d\rho} \ln F(\rho, \alpha) - \psi(\rho) + \ln \rho + 1 \right] + \left[\ln s_j - s_j \right] \right\} = 0. \quad (36)$$

The first term in square brackets is independent of j . This function, along with its variance, is calculated and tabulated

by Perkins. Therefore the quantity

$$L_{s,\alpha} = -\frac{1}{N} \sum_{i=1}^N (\ln s_i - s_i) \quad (37)$$

can be computed for those N values of $s_i \geq \alpha$ and compared with the tables to extract ν and the variance, $\Delta\nu$. For our sample of 1240 E1 intensities this method yields $\nu = 1.38 \pm 0.11$. A fit to the data for this value of ν is shown in Figure 22 where the data have been plotted as a function of the variable $x = \sqrt{s}$. $p(x, \nu)$ for $\nu = 1$ and 2 have also been plotted. The distribution is clearly not fit by $\nu = 1$ or 2. The fit for $\nu = 1.38$ is quite reasonable except for an excess of levels at $x \approx 1.8$. This bump cannot be fit with any single chisquared distribution.

Wasson et al.¹⁵ extracted a ν from a set of 50 transitions from nine resolved resonances giving a total sample of 450 transitions. Since they did not know the final state spins and parities they performed Monte Carlo calculations with a model assuming M1 and E1 transitions between states distributed with a $(2J+1)$ level density dependence for both initial and final states with the appropriate selection rules applying and compared these results with their data. They found $\nu = 0.75^{+0.23}_{-0.13}$ for the results of their analysis.

Statistically, if the distribution for resolved transitions follows a chisquared distribution with one degree of freedom, the distribution for an unresolved multiplet with n components will follow a chisquared distribution with n degrees of freedom. To verify that the value of ν extracted in this experiment was not contaminated by unresolved E1 doublets, the data were subdivided into 100-keV bins in γ -ray energy and the fitting

procedure repeated. The results are plotted as a function of E_γ in Figure 23. Since the sample size is now much smaller, the variance of ν is much larger. The results are consistent with no energy dependence of ν and no increase in unresolved doublets as the excitation energy increases.

The strength function was extracted from these same 100-keV bins and is plotted in Figure 24. In this limited range of γ -ray energy the results are consistent with an E_γ^3 dependence for the intensities, with $\langle S \rangle = (1.25 \pm 0.07) \times 10^{-7}$ over the entire data set. The Brink-Axel hypothesis^{1,2,6} predicts an E_γ^5 dependence for the E1 intensities as obtained from the tail of the (γ, n) giant dipole resonance in this energy range. The dotted line shows an E_γ^5 dependence. Least squares fitting of the data $S_i E_i^3$ to the function $A x^b$ gives an exponent $b = 2.52 \pm 0.61$, which is consistent with E_γ^3 .

Figure 25 compares the strength function from the present experiment with the 0.7 MeV $^{181}\text{Ta}(n, \gamma) ^{182}\text{Ta}$ data of Earle et al.⁴² and the average-resonance of L. M. Bollinger, J. R. Erskine, and G. E. Thomas.⁴³ The Bollinger data are unpublished and were taken from a figure published by Jackson.⁴⁴ The data were plotted in arbitrary units for transitions to $(3^-, 4^-)$ and $(2^-, 5^-)$ states. The points plotted were derived by averaging $(I_{3,4} + 2 \cdot I_{2,5})$ for points in 200-keV bins and normalizing the average over the 5 to 6 MeV range to the present results. The data of Earle et al.⁴⁵ were obtained from measurements of the γ -ray spectra from capture of 0.7-MeV neutrons using NaI detectors, subsequent unfolding of the detector response, and correction for cascade γ -rays. In the energy

range from 5 to 6 MeV, the present results are consistent with the energy dependence of both Bollinger *et al.*⁴³ and both the energy dependence and absolute magnitude of the data of Earle *et al.*⁴⁵ Between $E_\gamma = 4$ and 5 MeV there is a major discrepancy. The prediction of Bartholomew *et al.*,² based on the tail of the (γ, n) giant resonance, is shown as the dotted line.

In addition to the 19 resolved neutron resonances, the spectra were summed over the neutron energy groupings: 20 to 100 eV, 100 to 200 eV, 200 to 400 eV, 600 to 1000 eV, and 1000 to 3000 eV. γ -ray peak areas and centroids were extracted by the automatic peak fitting routines for these groups. Each of the spectra was treated on its own merit. No attempt was made to use the detailed peak-fitting method employed for the resolved resonance data. The data were converted to energies and photons/1000 captures in the same manner as for the resolved resonance data.

Seven transitions, not seen in the resolved resonance data, were observed in one or more of the averaged spectra. They are indicated with an "*" following the energy in Table II. Two of these transitions are to 4^+ final states observed by Helmer *et al.*¹⁶ The rest are assumed to be positive parity states also, but no J^π assignments were attempted. In some instances, where there was not a clear distinction between E1 and M1 transition strengths in the resolved resonance data, a distinction can be made from the intensities of the averaged data. These levels are indicated in Table II by a "***" following the recommended J^π value.

To study the variation of the average intensity as a function of neutron energy, the intensities were summed in 100-keV bins and listed in Table III as photons/1000 captures/MeV. These include both E1 and M1 transitions. The number of E1 transitions missing in each bin for the average spectra was noted and where no more than 50% were unobserved, the intensity in parentheses was computed by multiplying the observed intensity by the ratio of the total number of E1 transitions in the averaging bin to the number observed. The number of unobserved transitions increased rapidly as a function of both excitation and neutron energy. As the excitation energy increased the spectra became more complex, and as the neutron energy increased statistics were poorer, the resolution broadened slightly and the backgrounds increased.

In the region where a sufficient number of E1 transitions was observed, with the exception of the group at lowest excitation, the agreement between the average intensity from the 19 resolved resonances and the intensities averaged over neutron energy was generally within the uncertainties of the experiment and/or the statistical fluctuations due to the finite number of transitions involved.

The strength function we obtained from the resolved resonance data is shown in Figure 24 and listed in the column labeled " S_0 " in Table IV. We wished to see if we could extract a strength function from the average intensities listed in Table III and see how well the results compared with the detailed analysis of the discrete results.

If we ignore M1 transitions, assume a $(2J+1)$ level density dependence as given by eq. (23) for both initial and final states, and use the dipole selection rules, it can be shown that

$$S(E_\gamma) = \frac{2}{3} \frac{\Gamma_\gamma}{D} \frac{(I(E_\gamma)\Delta E_\gamma)}{N_\gamma E_\gamma^3} \text{ MeV}^{-3}. \quad (38)$$

Here $\bar{S}(E_\gamma)$ is the E1 strength function; Γ_γ is the total radiation width for capture of neutrons; D is the level spacing of the 3^+ and 4^+ capture states; $I(E_\gamma)$ is the average capture intensity (photons/1000 captures/MeV) in the bin which is ΔE_γ wide at E_γ ; and N_γ is the total number of 2^- , 3^- , 4^- , or 5^- final states in the bin ΔE_γ wide. The values $\Gamma_\gamma = 55$ meV and $D = 4.4$ eV were used. The values of $I(E_\gamma)$ with $\Delta E_\gamma = 100$ keV were taken from Table III. N_γ was found by counting the number of negative parity states in the interval ΔE_γ in Table II.

The results are summarized in Table IV. A comparison of the columns " S_0 " and " $\langle S_{\text{res}} \rangle$ " provides a check on the method since the initial data are identical and only the method of analysis has changed. That is, for " S_0 " the S_{ij} from eq. (7) were calculated and then averaged over the energy bins to form " S_0 ". For " $\langle S_{\text{res}} \rangle$ ", the intensities were averaged first and then eq. (23) applied. Because the number of negative parity states in 100-keV wide bins, especially at low excitation, is too small for eq. (8) to be statistically valid, and M1 transitions were ignored, the frequent 30 to 40% differences were not unexpected.

Within the accuracy of the assumption of eq. (23) in the derivation of eq. (38), the results of the averaged value of the

strength function show no systematic variation as a function of neutron energy, with the exception of the group at lowest excitation. This anomalously high value becomes more consistent with the other values of the strength function at higher neutron energy, where more initial capture states are included.

In summary, if the level scheme is known, the strength function can be extracted with a $\pm 30\%$ reliability from spectra averaged over neutron energy. The range of γ -ray energy for which this can be done becomes severely limited in comparison with the resolved neutron resonance technique because of the high density of final states at high excitation.

B. Unfolding of γ -ray Spectra

The spacing of observable γ -ray lines becomes similar to the detector resolution at 1.8 MeV excitation for the individual resonance spectra and at about 1 MeV for spectra summed over many resonances. Therefore it was not possible to extract average γ -ray intensities by summing individual lines for γ -ray energies less than about 5 MeV. However, information on the average γ -ray spectrum could be obtained by unfolding the observed spectrum using the measured response function of the three-crystal spectrometer.

The response function was determined by measuring the response of the three-crystal spectrometer to photons of 2250-, 2615-, 4430-, and 6142-keV energy as described in the section on the details of the experiment. Figure 26 shows a typical response function with the separate components indicated. The labeled functions give the fraction of the total counts in the response, per unit energy, as a function of the energy deposited, E_d .

It was observed that the labeled functions in Figure 26, $f_{1e}(E_d)$, $f_l(E_\delta - E_d)$, and $f_u(E_d - E_\delta)$ were, within experimental error, independent of the incident photon energy. (E_δ is the energy of the double escape peak.)

The flat portion of the response, f_c , had a small energy dependence that was approximated by the linear relationship

$$f_c = 1.19 \times 10^{-4} - 5.67 \times 10^{-9} E_\delta(\text{keV}). \quad (39)$$

The peak response, f , was assumed to be a delta function at energy E_δ with amplitude $\alpha(E_\delta)$.

The entire response was integrated over E_d giving,

$$1 = \alpha(E_\delta) + \int_0^{E_\delta} f_c(E_\delta) dE_d + \int_0^{E_{th}} f_{le}(E_d) dE_d + \int_{E_\delta}^{E_\delta} f_l(E_\delta - E_d) dE_d + \int_{E_\delta}^{E_u} f_u(E_d - E_\delta) dE_d. \quad (40)$$

As parameterized, the last three integrals are independent of E_δ and were numerically integrated from the experimental values of the ^{228}Th response. The integral of f_c was readily evaluated using eq. (39) to give an analytic expression for $\alpha(E_\delta)$,

$$\alpha(E_\delta) = 0.776 - 1.19 \times 10^{-4} E_\delta + 5.671 \times 10^{-8} E_\delta^2. \quad (41)$$

Figure 26 compares eq. (41) with the experimentally determined values of α . The agreement is satisfactory and eq. (41) was used to calculate α in the unfolding program.

The usual technique for unfolding a γ -ray spectrum involves calculation of the response matrix with subsequent inversion to determine the spectrum.⁴⁶⁻⁴⁹ This requires the manipulation of very large matrices for these data. Since the response function for this experiment is simple ($\approx 30\%$ of the response is a delta function at the double-escape peak energy), a technique using successive unfoldings was developed which avoids the need for matrix inversion.

The features of this technique are as follows. The spectrum, with uncertainties, is read into arrays C, ΔC . The energy region of interest is divided into 120-keV wide bins. For each bin the criteria for subtracting the response due to the counts in a given channel were based on the values of the following quantities in the bin. The residual for each channel is defined

as $\Delta C/C$ and the average residual $\bar{R}$ and maximum residual are computed. This procedure starts with the highest energy group. If the maximum residual is greater than one or the average, $\bar{C}$, greater than 0.1, then the response for those channels whose counts are greater than $\bar{C}$ are subtracted from the array C as follows. A portion, $0.75 \cdot C_i$, is assumed due to the delta function and transferred to the array GC_i . The rest of the response function, with amplitude $0.75C_i/\alpha$, is subtracted channel by channel from C and added to an array CC. This procedure is reiterated until the average residual is less than 0.1 and the maximum residual less than one for each region. The γ -spectra can now be computed by applying the detector peak efficiency and normalization constant to the array GC and shifting the energy coordinate by 1022 keV to transform from double-escape energies to incident photon energies.

The spectra which were unfolded were taken with a 14.3-cc Ge(Li) detector in a three-crystal spectrometer at 13.47 m flight path. The sample was a 50- x 100-mm sheet of Ta, 3.175 mm thick. The total running time was 101 hours with a 100-MeV, 720-Hz, 100-nsec wide beam with 100 μ A average current. To extend the neutron energy range to 90 keV, it was necessary to use a shadow bar.

Figure 28 shows the results of the unfolding of a typical spectrum, with the unfolded peak counts and the unfolded continuous portion of the response plotted versus the energy deposited in the detector. The results have been averaged into 100-keV bins. The residuals are plotted at the bottom of the graph. Although the residuals do show some systematic devia-

tions from zero, the absolute magnitude of the deviation is small.

After averaging, a background was subtracted from the data. This background had two components. The first was due to out-of-time neutrons. It was determined by using the between-resonance spectra and subtracted with an amplitude proportional to the time-of-flight interval of each spectrum. The other component was due most likely to accidental coincidences between the three detectors. Its shape was estimated and the amplitude normalized to the unfolded spectra at low γ -ray energy.

The results of this unfolding are shown in Figure 29 for the neutron energy ranges 20 to 100 eV, 10^2 to 10^3 eV, 10^3 to 10^4 eV, and 10^4 to 9×10^4 eV. The uncertainties shown are due to both counting statistics and uncertainties in the background. The large uncertainties below 2-MeV γ -ray energy are due mostly to background uncertainties. The intensities were normalized to the 4.28-eV resonance results of Wasson et al.¹⁷ using the same method described in Section IV-A. In the region of overlap between the two experiments the agreement of the intensities is excellent.

The four spectra are essentially identical, within error bars, for photons of less than 5 MeV. Above 5 MeV there is a systematic decrease in strength with increasing neutron energy. The bump at $E_\gamma = 4$ MeV, which persists for neutron energies between 20 and 10^4 eV, is due to a local clustering of γ -ray lines, not a single transition.

Figure 30 compares the $E_n = 10^2$ to 10^3 eV spectra with the shape of a calculation by Gardner.⁵⁰ In this calculation the

Brink-Axel hypothesis was used to describe the E1 strength function as the tail of the E1 giant resonance. Discrete levels of definite spin and parity were used below 0.5 MeV excitation in ^{182}Ta , and level density formulas were used for higher excitation. The formalism for the level densities was taken from Gilbert and Cameron⁵¹ as

$$\rho(E, J) = (2J+1) \frac{\exp(-(J+1/2)^2/2\sigma^2)}{2\sqrt{2\pi} \sigma^3} \rho_E(E) \text{ MeV}^{-1}$$

where $\rho(E, J)$ is the level density for state of spin J at excitation E , and σ is the spin-cutoff parameter. The term, ρ_E , gives the dependence on excitation energy. For excitations between 0.5 and 3.5 MeV, the constant temperature model,

$$\rho_E = \left(\frac{1}{T}\right) \exp \left[(E-E_0)/T \right],$$

was used, and above 3.5 MeV the Fermi gas model,

$$\rho_E = \frac{\sqrt{\pi}}{12} \frac{\exp\{2\sqrt{aE}\}}{a^{1/4} E^{5/2}}.$$

The parameters were taken from Gilbert and Cameron.⁵¹

The agreement in the shape of the measured and calculated spectra is reasonable, although the data shows a 10 to 20% excess of γ -rays in the 4 to 6 MeV region. This most likely reflects the deviation of the strength function from the Brink-Axel hypothesis.

The calculation was adjusted upward by a factor of 1.5 to normalize the shape to the data. The thermal capture data of Orphan et al.,³⁴ for Ta are a factor of about 1.5 lower than the present results. This discrepancy is related to the value found for the absolute intensity of the ground state transition

for thermal neutron capture. The value of Wasson et al.,¹⁵ to which the present data are normalized, is $I_{G.S.} = 6.2 \pm 1.0$ photons/1000 captures. The value of Orphan et al. is 4.4 with no uncertainty quoted. When this discrepancy is resolved, all intensities quoted in the present results can be renormalized to the best value of $I_{G.S.}$ merely by multiplying them by $I_{G.S.}/6.2$.

V. Summary

High resolution measurements of the spectra of γ -rays from the capture of neutrons by ^{181}Ta were made in the neutron energy range from 2 eV to 9×10^4 eV using a three-crystal spectrometer. Data analysis codes and techniques were developed to extract the energies and intensities of resolved γ -ray transitions from the large arrays of experimental data which are obtained using the time-of-flight technique at a linac. A method was also developed for unfolding the simple response of the three-crystal spectrometer from the measured data. This allowed the average capture γ -ray spectra to be extracted in the 1.5 to 6.1 MeV range.

Electromagnetic selection rules allowed spin and parity assignments to be made over a large range of excitation energy. Ninety negative parity states were observed below 1.8 MeV excitation in ^{182}Ta . An additional 20 positive or undetermined parity states were also found in this excitation region. Spins were determined to be 2, (3,4), or 5. Thirteen previously unreported states were observed below 1450 keV excitation. The measured level scheme is essentially consistent with previous work below 600 keV excitation, but the present results allow more reliable spin and parity assignments above this energy. (Thirty-eight additional levels were observed above 1450 keV but there is no previous data with which to compare.)

A set of 1240 partial radiative widths were extracted for E1 transitions and fit with a χ^2 distribution. The result of this analysis was 1.38 ± 0.11 degrees of freedom, which is not consistent with the prediction of the extreme

statistical model ($\nu = 1$). This effect has also been observed for heavy nuclei by other workers. (See references 4, 10, 13, 14.)

The E1 strength function was measured by averaging resolved, absolute E1 transition strengths for γ -rays between 4 and 6 MeV. The results are consistent with previous results near the binding energy but show marked deviations in the 4- to 5-MeV region. In particular, for the entire 4- to 6-MeV region the strength function is more consistent with an E_γ^3 energy dependence than with the E_γ^5 dependence predicted by the Brink-Axel hypothesis. An anomalously high strength for transitions to states in the first 100 keV of excitation was observed for the resolved resonances that was not present in the average strength function that was extracted at higher neutron energies.

The spectral data for broad bands of neutron energy between 2 and 9×10^4 eV were unfolded using the simple response function of the three-crystal spectrometer and the absolute average intensities were extracted. The results agreed well with the resolved transitions data in the region of overlap. Between 1.5- and 5-MeV γ -ray energy the spectra were essentially the same for all incident neutron energies. However, above 5 MeV there was a definite decrease in strength as the neutron energy increased.

In conclusion, it has been demonstrated that the simple response of the three-crystal spectrometer allows capture γ -ray spectra to be measured with more versatility than other techniques. In particular, the level scheme of ^{182}Ta has been extended to higher excitation energies, more reliable spin and parity assignments have been made, and the distribution of

partial radiative widths has been analyzed with a greater degree of accuracy than in previous work. The E1 strength function has been extracted in a straightforward manner to provide accurate data on its form in this energy region of 4 to 6 MeV. Finally averaged γ -ray spectra have been extracted for a large range of neutron and γ -ray energy to provide nuclear data which are useful in reactor design and radiation transport studies.

The γ -ray detector and data analysis techniques developed for this thesis problem can be used for studies of other nuclei with high final state level densities. In particular, the accurate measurement of the partial radiation widths which can be obtained with this system makes it possible to study nuclei where deviations from the statistical model of the nucleus either have been observed or are expected. For applied physics problems, averaged γ -ray spectra can be obtained above 1.5 MeV for a wide range of nuclei with less uncertainty than other existing techniques.

Appendix I -- Data Analysis Codes

A detailed description of the set of data analysis codes used in this experiment will be given. Common to the system of codes is a collection of subroutines used to facilitate various input/output functions. These subroutines will be described first, followed by a description of the data analysis codes.

1. General Input/Output Subroutines

Many of the codes are run in an interactive mode where the routine requests information from the user by sending questions via teletype. Responses can take the form of numbers, names, alphanumeric text, or (yes or no) answers. The master operating system enables both text (an arbitrary string of alphanumeric characters) or symbols (contiguous, nonblank text of ten or less characters) to be transferred easily to the program. Functions were written to operate on these messages so that format-free input was obtained.

It was frequently necessary to input arrays of numbers of the following form: n points with coordinates (x_i, y_i) and possibly an uncertainty, Δy_i , associated with the y -coordinate from a diskfile of ASCII card images. A routine, RABCDL, was developed to read a format-free file of this form into the computer with the arrays stored in specified common blocks.

Frequently it is possible to reduce the effective program size and increase efficiency by dividing the program into main and overlay segments. Only the portions of the code that are needed for a particular task are brought into core at the time

they are needed. Routines were written to control the transfer of the overlays and reduce the program to the minimum size needed.

Because of the large number of data points occurring in the raw data, large blocks of memory and disk would be used if this information was stored as one channel of counts per 60-bit word. Therefore the data, where integer representation was appropriate, were packed so that more than one integer was contained in a 60-bit word.

For 1-D data, each word, i , in an array, $NDATA$, was structured so that the first 24 bits contained the integer number of counts for the i th channel. The next 14 bits contained four times the error associated with that channel, and the final 32 bits were reserved for integer variables as required in any particular program. Since each channel is represented by the address of the word in the array and the variables can be extracted by a simple operation (i.e., rotate and mask), this provides a simple and efficient way of compressing and extracting the data. A common block was defined with the fixed form, $ID(6)$, $NCHAN$, $NDATA(ND)$ where ND is the dimensionality of the data, $NCHAN$ the number of channels, and ID contains 60 characters of alphanumeric identification. The routines $WDSKD$ and $GWSKD$ were written to create a disk file and transfer the common block to disk, and to transfer from disk back to the common block.

Similar considerations hold for 2-D data, but because of the generally large size of the arrays, the entire array cannot be transferred into core at one time. Therefore, a disk file (or family of disk files) was created with the following form.

Words 1-6 of each file were reserved for identification and words 7 and 8 were IXD and IYD, the x and y dimensionality of the data. The rest of the words were blocks, IXD long, of two-dimensional data. In the jth block, the ith word contains three 20-bit groups corresponding to the ith channel for the x coordinate. The first through third 20-bit groups in the word correspond to the $k = 3j+1$, $3j+2$, and $3j+3$ channels for the y coordinate. Thus, if a block IXD long, containing the desired y coordinate is transferred to a buffer, the contents C_{ik} for a particular x,y descriptor can be extracted from location i with simple rotate and mask operations that depend only on the modulus of k.

A third binary file form (TOFFILE) contains floating point data of the form E_i , R_i , DR_i , where these are the energy, rate, and uncertainty associated with the ith point of one-dimensional arrays. Each TOFFILE has words 1-6 reserved for identification. Words 7 and 8 are NEL and NDP. NDP is the number of data points in the arrays, and NEL is 2 or 3 depending on whether or not the errors, DR_i , are to be included. The routines RDSKFL and WTDTD read and write disk files to and from common blocks which have the form ID(6), NEL, NDP, E(ND), R(ND), DR(ND) where ND is the maximum dimensionality of the data. Only the first word of the common block and ND needs to be specified for the proper transfer.

Plotting of the data points on CRT and Calcomp plotters is an option in many of the programs. Subroutines were written to allow plots of N data points starting at a specified location in the arrays E, R, DR or I, C, DC. Options were included to plot the data with either linear or logarithmic scaling, plot the

square root of R or C, plot error bars, interpolate between points and to label the axes. For CRT plots scales were chosen automatically. For the Calcomp plots, the scales, as well as additional parameters such as size, plotting characters, etc., were input parameters.

Another frequent need is for least-squares fitting of a set of data with some functional form, either to parameterize the data in a convenient functional form or to extract parameters for comparison with theory. Some examples are finding the energy calibration curve for a Ge(Li) detector, efficiency calibrations, and extraction of peak areas and centroids from spectra.

Since the range of applications is broad and a nonlinear fitting procedure rather complicated, it was decided to write the fitting program, SEARCH, as a subroutine that could be interfaced as easily as possible with a wide variety of programs. This was done by defining common blocks for the data and the majority of the parameters, and by constructing two subroutines, FITFUNC and DPARAM, for each application which serve as a convenient interface between the calling program and SEARCH. FITFUNC (NFUN,X) computes the function (numbered NFUN) for the value x. The parameters of the function are entered in common blocks shared by FITFUNC, DPARAM, and the calling program. DPARAM serves to equivalence the parameters used by the SEARCH routine with those defined in the calling program and to define the desired accuracies of the parameters of the fit. Since it is often necessary to fix a parameter and not search on it, an array, NOP(I), is defined which selects the indices of the

parameters chosen for variation in the fitting procedure.

The search routine is based on a modification of the method of Marquardt³⁶ as developed by Bevington³⁷ with modifications to allow constraints to be more easily applied and to achieve more rapid convergence. This method will be described in section 3-b of this appendix.

2. Raw Data Conversion Codes

A brief description of the individual programs follow:

a) Linac formats to CDC-6600 formats.

The DCON- series convert data from various input media to 1-D or 2-D files. At the linac it was found that there was a need to convert data from a variety of formats to a form compatible with the CDC-6600 data analysis system. Some multi-channel analyzers produced no output other than a printed paper tape. The easiest way to convert this data to computer-compatible form was by punching a corresponding format-free card deck. A 4096-channel TMC analyzer produced a BCD (binary coded decimal) magnetic tape. The PDP-8 and PDP-15 computers could be programmed to produce a binary record of the data on magnetic tape with header words on each record indicating run number, record length, and record number. Occasionally, partially analyzed data in the form of a CDC-6600 disk file with one integer count/6500 word would be produced for conversion to 1-D file format. The program, DCONB, was written to convert these various formats to 1-D file form.

The routine runs interactively, asking the user questions as to the source and format of the data. Extensive checking for input errors and consistency of the data is done. The routine

has the capability of searching a magnetic tape for a requested run. When the data has been found and decoded, the user is requested to type in the identification and the name of the output file, and that file, with counts and errors based on Poisson statistics, is created.

The majority of the neutron physics data at the linac is accumulated on the magnetic drum which is associated with the PDP-15 computer. Here the data are written from the drum to magnetic tape in records corresponding to the length of a drum track (i.e., 3072 18-bit words long). The data can be separated on tape by EOF (end of file) marks. No identification is provided.

The program, DCON15, was written to decode 1-D data files from drum. This program runs interactively, requesting information to get to the beginning of the file containing the desired data and the octal starting address and length of the data in the file. After extraction and decoding, information for identification and output-file-name is requested.

DCON2D is a similar program for decoding two-dimensional drum data. If more than one tape is necessary to contain the data, the program will request the second tape to be hung upon encountering an EOF mark before completion of the extraction of the data. Besides the information needed to find the data file on tape, the program requests octal information on the starting address and the x and y dimension of the data in the tape file as well as the dimensionality with which it is to be stored on the output disk file. The program also requests a family file name and identification. Due to the problem of finding large,

contiguous blocks of available CDC-6600 disk space, the output file is divided into a family of files, 8^6 words long, if the data exceeds that length. Each disk file has the family name suffixed with 0, 1, 2 ... as necessary.

b) Preliminary view of the raw data

A series of codes prefixed DTLK- are concerned primarily with manipulation, editing, and display of data in the form of counts vs channel. The codes, DTLK2D and DTLK2DCI, are designed to extract a 1-D data file from a 2-D file. They differ only in that the first receives its commands interactive γ from teletype and the latter takes its commands from a disk file containing card images.

Operations such as extraction of resonance γ -ray spectra, between resonance γ -ray spectra, and dynamic pulse-height biasing for time-of-flight data can be done. A 1-D file is constructed for a specified direction. For example, a slice in the x direction is constructed so that for the i th channel,

$$C_j = C_i + \sum_{j=j_1}^{j_2} C_{ij}$$

where j_1 and j_2 define the range of y coordinates to be summed. Options for editing the data via teletype and producing printouts and plots of the 1-D spectra produced are provided.

DTLK1D and DTLK1DCI are codes that read 1-D files and provide a variety of options for manipulating, editing and examining the data. (CI refers again to card input rather than teletype.) With these codes it is possible to add and subtract runs with arbitrary normalization constants. Data can be compressed into

a smaller set by adding a specified number of adjacent channels between specified limits. The data can be edited from teletype. A $(2n+1)$ binomial smoothing of the data can be accomplished by n consecutive three-channel binomial smoothings. The titles can be changed and listings and plots of the data are optional.

- c) Conversion of time-of-flight data to rate vs neutron energy.

TOF1 reads data from 1-D files and converts the (counts/channel vs channel) information to a deadtime corrected (count rate/microsecond of time-of-flight vs neutron energy) form.

- (i) Conversion from channel to time-of-flight.

The time scale is determined by specifying the number of different time widths/channel in the data, the widths and beginning channels of those intervals and the absolute time (relative to the electron pulse striking the target) of the first channel. The time centroid of each channel can then be calculated.

- (ii) Deadtime corrections.

From the application of Poisson statistics⁵² to the observed counts/beam burst, C'_n , as a function of time-of-flight, the true counts/beam burst, C_n , can be related to the observed count rate by the relationship⁵³

$$C_n = -\log_e \left\{ 1 - C'_n / \left(1 - \sum_m C'_m \right) \right\}, \quad (42)$$

where C'_m refers to the count rate in all channels m that contribute to losses in channel n . Since eq. (42) is unsuitable for computation at low count rates, it was

expanded about 1 to second order. Three cases are considered. First, where the time analyzer has a fixed dead-time, T_d , the sum extends from channel n at time T to the channel at $T - T_d$. The second case is where only one pulse per beam burst is accepted. Here the sum extends from channels 1 through n . The last case is where all events with more than one pulse per beam burst are rejected. The sum extends over the entire range of data and consequently the correction is a constant, independent of channel. Since for two-dimensional data portions are extracted which do not reflect the total count rate, an option was added so that the corrections, taken from the total summed spectra, could be applied to the extracted spectra.

(iii) Conversion to energy and rate.

The energy of each channel is now computed from the time, T , and the flight path, L , by the relationship derived in the experimental section:

$$E_n(\text{eV}) = 5227 \frac{L^2(\text{m})}{T^2(\mu\text{sec})} . \quad (43)$$

The count rate, R_i , is computed as

$$R_i = \frac{NC_i}{\Delta T_i} , \quad (44)$$

where N is an arbitrary normalization constant and ΔT_i is the width (in μsec) of the i th channel. The fractional error is given by

$$DR_i = \frac{\Delta C_i}{C_i} , \quad (45)$$

where ΔC_i is the error associated with the counts in

channel i.

When the computations are complete a TOFFILE is created and the arrays transferred to disk. Listings and plots of the rate vs neutron energy are produced.

d) Conversion of data to cross sections.

This is done with a program called TOF2. In time-of-flight experiments it is frequently necessary to perform operations on the data such as subtracting backgrounds, taking ratios of runs, dividing by fluxes, and multiplying by the cross section of the flux monitor. In the case of total cross section measurements, the transmission must be formed and the total cross section computed from the transmissions. TOF2 was developed to perform these calculations with errors estimated for the results. The basic computation performed by TOF2 is

$$R(E) = N \frac{R_1(E) - B_1(E)}{R_2(E) - B_2(E)} E^{\eta} S(E). \quad (46)$$

The arrays subscripted 1 and 2 generally refer to the cross-section rates and flux rates respectively, and B refers to the associated backgrounds. S(E) relates to the flux-rate associated cross section and N and η are arbitrary constants. The points R(E) are computed at the points E_i of the array $R_1(E_i)$ and the values of the other quantities determined by linear interpolation in the arrays. The arrays R_1 , B_1 , R_2 , B_2 can be multiplied by arbitrary normalization constants. Options are available to skip portions of eq. (46) and to provide printouts and plots at intermediate stages. If the flux does not contain fine structure an option is available for averaging the flux

over a preset interval (as a function of energy) before dividing into the rate. An output disk file of the form TOFFILE is generated so the output of TOF2 can be fed back into itself for repetitive computation of eq. (46).

e) Averaging and plotting of the data.

The series of programs prefixed PNA- is designed to read files of either 1-D (PNAD) or TOFFILE (PNAT) form and to perform editing, averaging, listing, and plotting functions. The plotting can be done on CRT or Calcomp plotters. Ranges of the data and scales are chosen by the user to produce high-quality plots. TOFFILE output is optional.

PNAD converts the input data from 1-D to TOFFILE form via a functional relationship between energy and channel. Averaging can be done by averaging N adjacent channels between channels $I1$ and $I2$. N , $I1$, and $I2$ are input from teletype.

PNAN has two additional modes of averaging. DELTAE reads a card file containing a list of ΔE_i vs E_i and averages the data into bins ΔE wide as a function of energy with linear interpolation in E . ENAV averages the data into bins whose boundaries are determined by the list, E_i , read from a card file.

3. γ -ray peak-fitting routines.

a) Method of Marquardt

If we have a set of N data points X_i , Y_i , with errors, σ_i , and a function $f(x, p_1, p_2, \dots, p_m) = f(x, \bar{p})$, the best fit of the function to the data is defined as the set of parameters $\bar{p}$ such that

$$\chi^2 = \frac{1}{N-m-1} \sum_{i=1}^N \frac{1}{\sigma_i^2} (y_i - f(x_i, \bar{p}))^2 \quad (47)$$

is minimized.

If the function f is linear in the coefficients $\bar{p}$, χ^2 can be differentiated with respect to each coefficient p_i , set equal to zero, and a set of normal equations developed for a direct solution of $\bar{p}$.

If the equations are nonlinear in $\bar{p}$ then a more sophisticated, iterative procedure must be found to find the parameters at the minimum.

Let us expand the function, f , about an initial guess $\bar{p}_0$. To first order

$$f(x, \bar{p}) = f_0 + \sum_{j=1}^m \frac{\partial f_0}{\partial p_j} \delta p_j. \quad (48)$$

At minimum

$$\frac{\partial(\chi^2)}{\partial \delta p_k} = \sum_{i=1}^N \left\{ \frac{1}{\sigma_i^2} (y_i - f_{0i} - \sum_{j=1}^m \frac{\partial f_{0i}}{\partial p_j} \delta p_j) \frac{\partial f_{0i}}{\partial p_k} \right\} \quad (49)$$

for each parameter k . This can be expressed as a matrix equation

$$\bar{\beta} = (\alpha) \bar{\delta p} \quad (50)$$

where

$$\beta_k = \sum_{i=1}^N \frac{1}{\sigma_i^2} (y_i - f_{0i}) \frac{\partial f_{0i}}{\partial p_k} \quad (51)$$

and

$$\alpha_{jk} = \alpha_{kj} = \sum_{i=1}^N \left(\frac{1}{\sigma_i^2} \frac{\partial f_{0i}}{\partial p_j} \frac{\partial f_{0i}}{\partial p_k} \right). \quad (52)$$

This normal equation can be solved for $\bar{\delta p}$ to get a new predictor $\bar{p} = \bar{p}_0 + \bar{\delta p}$ and the procedure can be reiterated with the new guess $\bar{p}_0 = \bar{p}$ until convergence is achieved.

If the initial guess is sufficiently close to the final value, the procedure works well. If not, the resultant may lead to a larger value of χ^2 . To overcome this difficulty the following procedure was developed by Marquardt.³⁶ Since the diagonal elements of the matrix, α , are proportional to the gradient of χ^2 , weighting of those elements will force the predictor in the direction of the gradient. Therefore, the diagonal elements are weighted by $(1 + \lambda)$ where λ is initially set to 10^{-2} on the first cycle and 10^{-6} on subsequent cycles. If χ^2 increases on a particular cycle λ is multiplied by ten and the cycle reiterated. In addition, although the direction of $\bar{\delta p}$ is toward a minimum, the magnitude of $|\bar{\delta p}|$ may not be correct. Therefore a search using parabolic fitting is done on the parameter ϵ , so that the final $\bar{\delta p} = \epsilon \bar{\delta p}$. This procedure gives rapid, dependable convergence. The standard deviation in the parameter p_k is computed as

$$\sigma_{p_k} = \sqrt{\alpha_{kk}^{-1}} \text{ if } \chi^2 \leq 1 \quad (53a)$$

and

$$\sigma_{p_k} = \sqrt{\alpha_{kk}^{-1}} \chi^2 \text{ if } \chi^2 > 1. \quad (53b)$$

If the fitting function is linear in the parameters, $\bar{p}$, then the exact solution is found at the end of one iteration if $\lambda = 0$. Therefore, when the equations are linear, an argument is set to allow this procedure to be followed.

The derivatives with respect to the parameters are normally computed analytically in a routine FITFUNC. If this is not possible an option is allowed in SEARCH to compute them numerically.

b) Peaks fitting codes.

The area and centroids of various γ -ray lines were extracted from the spectral data using either eq. (8) or eq. (13). Since parameters describing the peak widths, step function and tailing portion of the response are not known a priori, it is necessary to allow these parameters to be varied in fits to selected peaks until the functional relationships can be determined. Once the functional form has been found for these parameters, only the parameters of peak positions, areas, and background are left free. In addition, for the resonance data, once a complete list of all peaks has been compiled, it is necessary to refit the data with all peaks included (at fixed positions) to get the complete set of partial radiation widths. It was decided to automate these procedures as much as possible. Because of the restricted nature of parts of the analysis, some codes in this group were written to perform restricted computations.

The most versatile code is PKSCCN. Because of the variety of computations to be performed, extensive use is made of MAIN-OVERLAY-SEGMENT loading to assure only the needed subprograms are in core at any given time and thus reduce the effective program size. Packing several integer variables into the same word is used for the same purpose.

The input spectra are of the 1-D file form. The code receives from teletype the information on the range of channels

to be fit MNC, MXC, and control parameters for fitting single peaks, printing results of intermediate stages of analysis, and allowing variation of the step function parameters. The sensitivity threshold for peak detection, SD (number of standard deviations), average peak width, FWHMA, energy calibration and parameters of the step function and tailing portion of the response are given next. The data points can either be unweighted, or weighted by the inverse square of the standard deviation of the data point, for the fit.

The first step in the analysis is the detection of peak regions. This is done in the subroutine FNDPKRG. Over the range, (MNC, MXC), the running average, NBK_i , is computed over 1.5 FWHMA channels on either side of, and including, the i th channel. If NBK_i is less than $(C_i - SD \cdot \Delta C_i)$, where C_i and ΔC_i are the counts and error of the i th channel, then a flag is set. This running average and comparison is repeated using the previously calculated value of NBK instead of the counts if the flag is set for any channel in the range of the average. This procedure is reiterated until the array of flags does not change.

The array of flags is scanned, single-channel background regions rejected, and single-channel peak regions inspected to assure that they do not arise from spurious statistical fluctuations. The array of flags is rescanned with the beginning channel, ending channel, and channel of maximum counts defined for each peak region. The peak regions are examined, checked for statistical validity, extended to assure an adequate number of channels for background determination, and consolidated where necessary.

The arrays defining the peak regions are printed out and if the option is chosen, the data are plotted with the peak regions indicated on the plot.

The next option is fitting a single peak to each region, allowing the FWHM, w , to vary. The parameters of this fit to each region are optionally printed out and the fit plotted. The parameters of the fit, with their standard deviations, are stored in internal arrays.

The next option is to fit the array of widths, w_i , with the functional form:

$$w = \sqrt{a_w^2 + b_w x} \quad (54)$$

where x is the channel number. Points with large standard deviations or which are exceptionally large are rejected initially. The fit is examined and points which are not fit by eq. (54) (usually because the peak is a multiplet) are rejected one at a time until a consistent data set and fit is obtained. The results are plotted and printed out on teletype. The values of a_w and b_w can either be accepted or new values input from teletype.

The next stage is fitting multiple peaks (if needed) to each peak region with the parameters defining the width fixed. For each peak region the range of channels is carefully chosen to give a sufficient number of channels to define the background parameters. If necessary, adjacent peak regions are fit simultaneously. Peaks are injected initially at the channels of maximum counts, the region fit and the residuals examined. If the residuals exceed SD and are sufficiently positive over w

channels centered at the maximum residual, more peaks are inserted and the procedure reiterated until no more peaks are needed. The information required to fit the region is written on to a disk file called PUNCHFILE at each iteration and the fit plotted. PUNCHFILE is later edited to discard bad fits.

To reduce program size, subsequent peak-fitting routines had CRT plotting capability removed. The program MPPLT generated the plots from the 1-D data file and the PUNCHFILE.

The next program in the series is PCRIN. This program is the same as PKSCCN except that it takes input from card file rather than teletype and omits the single-peak fitting features of PKSCCN.

These two programs are about 95% effective in finding and fitting all observable peaks in the typical spectrum. For those cases where fits are not satisfactory, a code, TPKS, will generate fits with a fixed number of peaks to a given region with the starting parameters given via teletype. The PUNCHFILE output from TPKS can be merged with the PUNCHFILE from PCRIN or PKSCCN to provide a final set of fitting parameters.

When all observable peaks have been extracted from each resonance, a list of all observed peaks is compiled. The last fitting routine, PEAKSL, reads this list, a list of peak regions, and does a linear least-square fit to extract the area (with probable error) for each peak in the list for each of the spectra. Because of Porter-Thomas fluctuations some of these peaks will be unobservable in a given spectrum, and since a peak is constrained to a given position, the least-squares fitting routine will occasionally assign negative areas to these peaks. In this

case those peaks with areas more negative than their probable error are removed and the region refit. If there is more than one peak removed in a region the negative peaks are reinserted one at a time to get the best estimate of their areas while affecting the remaining peaks as little as possible.

The PUNCHFILE output can be edited to give a final list of all peak areas with their probable errors.

c) Conversions to energies and intensities.

These centroids and areas must have an energy calibration, normalization and efficiency applied to be converted to energy and intensity of a transition. The energy calibration is done with the program CALIB. CALIB accepts input of the form $(X_i, \Delta X_i, E_i)$ where $X_i, \Delta X_i$ are the centroid and error of the gamma of energy E_i and converts to $X_i, E_i, \Delta E_i$ assuming a linear fit for $E = f(x)$. Eq. (15) is fit to this data to extract the nonlinearity and energy calibration. A disk file, ECOEF, is formed giving the coefficients of the energy calibration. A printout of the calibration and a plot of the nonlinearity is produced.

The code, SPEAKS, with the detector efficiency entered in an evenly-spaced (in energy) array by DATA statements, reads the energy calibration from ECOEF. For each PUNCHFILE, it applies the energy calibration, Q value, and normalization to generate the final results

$$E_i = f(X_i), E_{di} = E_i + 1022.0, \Delta E_i = \Delta X_i \frac{df}{dx}(X_i),$$

$$E_{xi} = Q - E_{di}, I_i = \frac{N A_i}{\varepsilon(E_d)}, \text{ and } \Delta I_i = I_i \frac{\Delta A_i}{A_i};$$

where E_i is the observed energy of the γ -ray, E_{di} is the γ -ray energy assuming it is a double-escape peak, E_x is the excitation energy, I_i is the intensity and the quantities prefixed with Δ are the associated errors. These quantities are written on disk file for use by later data analysis programs.

4. γ -ray spectra unfolding.

As described in the results of unfolding the spectra, it was found that the response could be approximated as having more than 30% of the total response in a delta function at the energy of the double-escape peak with the rest of the response showing a rather smooth energy variation. The technique to unfold the spectra used the following method. Considering in succession the most prominent channels in the spectrum, a fraction of the counts was transferred to an array representing the delta function portion of the response, and the continuum portion of the response associated with the delta function transferred to an array representing the continuum. This procedure was iterated until both the maximum and average residual left in the original array was sufficiently small. The efficiency calibration was then applied to convert the unfolded counts to photons/capture/MeV. The various arrays were sent to disk in TOFILES for subsequent averaging and plotting by PNAT.

The response function was parameterized and entered as either functional relationships or evenly-spaced arrays via DATA statements in the routines CCALC and CSUB. The efficiency was entered via DATA statements in SET3X. The parameters XNORM, EMIN, EQQ, CEPC, SD and FRACT were entered via teletype. XNORM is the normalization constant for the unfolded data. EMIN and

EMAX provide the energy range for the unfolding, and E00 and CEPC give the linear energy calibration. SD is the size of the maximum residual at convergence and FRACT is the fraction of the counts in a channel in the spectrum being unfolded to be attributed to the delta function portion of the response. SD was set to 1.0 and FRACT to 0.75 for the final results.

The data were read in from a 1-D disk file and transferred to the array C. The probable errors were transferred to DC. The data were next divided into regions 120-keV wide and a flag associated with each region initialized at zero. When convergence was achieved for a region the flag was set to 1.

For each iteration the following procedure was used. The regions were examined in monotonically decreasing order of energy. If the flag was set, no counts were unfolded from that region. If convergence was not achieved, for each channel in the region that exceeded the average counts per channel of the region, $FRACT * C_i$ was transferred to the array GC_i . For each channel where the continuum portion of the response function was nonzero, the appropriate amount of the continuum associated with $FRACT * C_i$ was transferred to the array CC.

After each iteration, χ^2 and the average residual, CBAR, for the entire data set, and the array of flags was printed out. When the flags were all equal to one the unfolding was terminated, and the arrays printed out. The detector efficiency and the normalization were applied to GC and the arrays sent to disk in TOFFILE form for subsequent averaging and plotting by PNAT.

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List of 19 Resonances Analyzed for Resolved Transitions

	E_O (eV)	J^π	$2g\Gamma_n$ (meV)
1	4.28	4^+	4.4
2	10.34	3^+	4.08
3	13.95	4^+	1.14
4	20.3	3^+	1.15
5	23.9	4^+	6.5
6	30.0	3^+	0.22
7	35.2	3^+	9.3
8	35.9	4^+	16.9
9	39.1	4^+	44.9
10	49.2	3^+	1.05
11	63.1	4^+	5.8
12	82.9	4^+	14
13	99.32	3^+	115
14	{ 103.5 105.5	{ ? 3^+	{ 1.1 30 }*
15	115.1	4^+	41
16	126.5	3^+	8.5
17	166.4	4^+	112
18	194.8	4^+	40
19	200.0	3	

* Because of the large ratio of $2g\Gamma_n$ this was treated as a single 3^+ resonance.

TABLE II

LEVELS IN ^{182}Ta

Present results			Wasson et al. ^a		Helmer et al. ^b			Recommended
E_x	ΔE	J^π	E_x	J^π	E_x	ΔE	J^π	J^π
0.		$3,4^-$	0	3^-	0		3^-	3^-
16.9	0.7	5^+		U^c	16.5	0.4	5^+	5^+
90.2	1.7	$3,4,5^-$		U		U		$3,4,5^+ \text{***}$
98.2	0.5	$3,4^-$	98.1	$3,4$	97.80	0.02	4^-	$3,4^-$
114.6	0.5	$3,4^-$	114.1	$3,4$	114.33	0.02	4^-	$3,4^-$
149.9 ^d	1.1			U	150.4	0.4	4^+	
163.3		U		U	151.3	0.4	6^+	6^+
173.0	0.5	5^-	173.5	$3,4,5$	173.4	0.2	5^-	5^-
237.3	0.5	5^-	238.0	$3,4,5$	237.37	0.04	5^-	5^-
245.8 ^d	1.6			U		U		
251.5	1.0	$3,4^+$	250.5	$2,3,4$	250.2	0.4	3^+	$3,4^+$
270.1	0.5	$2,3,4^-$	270.1	$2,3,4$	270.4	0.01	2^-	2^-^d
292.5	0.4	5^-	292.6	$3,4,5$	292.97	0.03	5^-	5^-
317		U		U	317 ^e		6^-	
331.5		U		U	331.4	0.4	5^+	
334.8		U		U	334.8	0.4	7^+	7^+
359.6	1.3	$3,4^-$	361.3	$3,4,5$	360.53	0.4	3^-	$3,4^- \text{**}$
365.5	1.3	$3,4^+$		U		U		$3,4^+$
397.3		U		U	397.3	0.5	6^+	
402.65		U		U	402.65	0.02	2^+	
423.5		U		U	423.5	1.1	$2^+, 5^+ f$	
458.2 ^d	1.2			U		U		
474.4		U		U	474.7	0.7	3^+	
477.4	0.5	$3,4^-$	478.7	$3,4$	479.8	0.2	4^-	$3,4^-$
491.0	1.4	2^-	490.4	$2,3,4$	491.8	0.3	$2^-, 5^-$	2^-
505.4	0.6	5^+	505.2	$3,4,5$	505.4	0.2	5^+	5^+
519.7		U		U	519.7	0.4	10^-	10^-
547.0	0.5	$3,4^-$	546.9	$3,4$	547.1	0.2	3^-	$3,4^-$
559		U		U	559 ^e		1^-	
566.5	0.5	$3,4^-$	566.9	$3,4$	565.7	0.2	$3^-, 4^-$	$3,4^-$
571.8 ^d	2.2			U	571.5	0.7	4^+	
584		U		U	584 ^e		0^-	
586.6		U		U	586.6	1.2	$2^+, 5^+ f$	
627.8	0.5	5^-	632.9	$3,4,5$	628.4	0.2	5^-	5^-
650.5	0.5	$3,4^-$	650.9	$3,4,5$	649 ^e		4^-	$3,4^-$
659.2	0.5	$2, 3, 4^-$	659.3	$3,4,5$	659.6	0.4	2^-	2^-
662.8 ^d	1.0			U		U		

TABLE II (Cont.)

LEVELS IN ^{182}Ta

Present results			Wasson et al. ^a		Helmer et al. ^b			Recommended
E_x	ΔE	J^π	E_x	J^π	E_x	ΔE	J^π	J^π
667.9	1.4	2 ⁻	665.0	3,4,5	666.0	0.4	2 ⁻	2 ⁻
701.1	0.5	5 ⁻	700.1	3,4	702.0	0.2	3 ⁻	5 ⁻
719.6	0.5	3,4 ⁻	719.9	3,4	719.6	0.2	3 ⁻	3,4 ⁻
740.9	0.9	2,3,4 ⁻	740.0	2,3,4,5	740.3	0.3	2 ⁻	2,3,4 ⁻
777	U		U		777 ^e		7 ⁻	
781.9	0.5	5 ⁻	782.0	3,4,5	780.0	0.2	5 ⁻	5 ⁻
791.0 [*]	1.6		U		U			
816.7	0.5	3,4 ⁻	817.0	3,4	817.0	0.2	3 ⁻	3,4 ⁻
830.5 [*]	1.6		U		U			
835.9	0.5	3,4 ⁻	835.0	3,4	835.4	0.3	4 ⁻	3,4 ⁻
842.0	1.2	3,4,5 ⁻	844.0	2,3,4,5	843.3	0.2	3,4 ⁻	3,4,5 ⁻
856.1	0.5	3,4 ⁻	857.0		856.0	0.2	2,5 ⁻	3,4 ⁻ **
866.3	U		U		866.3	0.4	2,5 ⁻	
881.2	0.8	3,4,5 ⁺	881.4		881.6	0.4	3,4 ⁺	3,4,5 ⁺
897.5	0.5	3,4 ⁻	899.1		897.7	0.2	2,5 ⁻	3,4 ⁻
910.3	0.5	5 ⁻	912.7		910.0	0.2	3,4 ⁻	5 ⁻
914.7	0.5	3,4 ⁻	U		915.7	0.3	2 ⁻ ,5 ⁻	3,4 ⁻
935.8	U		U		935.8	1.3	(2-5) ⁺	
939.6	1.5	5 ⁻	940.0		939.9	0.2	2,5 ⁻	5 ⁻
960.0	1.5	3,4 ⁻	961.8		960.9	0.2	3,4 ⁻	3,4 ⁻ **
985.6	0.5	3,4 ⁻	987.0		986.6	0.2	3,4 ⁻	3,4 ⁻
999.8	0.8	3,4	U		1003.4 ⁱ	0.3	2,5 ⁻	3,4
1021.6	1.5	3,4 ⁺	U		U			3,4 ⁺ **
1028.4	0.6	3,4 ⁻	1029.4		1029.4	0.25	3,4 ⁻	3,4 ⁻
1049.9	0.9	3,4 ⁻	U		1050.5	0.3	3,4 ⁻	3,4 ⁻
1054.2	U		1054.2		U			
1056.6	0.5	3,4 ⁻	1057.1		1057.2	0.25	3,4 ⁻	3,4 ⁻
1082.0	0.5	3,4 ⁻	1082.9		1082.6	0.25	3,4 ⁻	3,4 ⁻
1101.2	0.8	3,4 ⁻	1101.5		1100.7	0.3	2,5 ⁻	3,4 ⁻ **
1113.6	0.5	5 ⁻	1114.3		1113.5	0.4	2,5 ⁻	5 ⁻
1125.0	1.5	5 ⁻	1126.3		1125.1	0.4	2,5 ⁻	5 ⁻
1136.9	0.6	3,4 ⁻	1138.1		1137.2	0.3	2,5 ⁻	3,4 ⁻
1150.4	0.5	3,4 ⁻	1151.4		1150.3	0.4	2,5 ⁻	3,4 ⁻
1170.4	0.6	3,4 ⁻	1170.5		1169.6	0.4	2,5 ⁻	3,4 ⁻
1196.0	1.0	2,3,4 ⁻	1197.8		1197.9	0.3	3,4 ⁻	3,4 ⁻
1203.1	1.8	3,4,5 ⁺	U		U			3,4,5 ⁺

TABLE II (Cont.)

LEVELS IN ^{182}Tl

Present results			Wasson et al. ^a		Halper et al. ^b			Recommended
E_x	ΔE	J^π	E_x	J^π	E_x	ΔE	J^π	J^π
1216.1	1.1	2 ⁻	U		1216.3	0.7	2,5 ⁻	2 ⁻
1229.7	0.5	3,4 ⁻	1236.6		1229.8	0.3	3,4 ⁻	3,4 ⁻
1240.4	0.5	3,4 ⁻	1242.2		1240.4	0.4	2,5 ⁻	3,4 ⁻
1260.1	0.5	3,4 ⁻	1260.3		1259.4	0.5		3,4 ⁻
1269.5	0.5	3,4 ⁻	1270.3		1270.3	0.5		3,4 ⁻
1279.8	0.5	3,4 ⁻	1281.1		1281.1	0.4		3,4 ⁻
1284.4	0.5	3,4 ⁻	U		U			3,4 ⁻
1289.5	U		U		1289.5	0.7		
1298.6	1.0	(2-5)	U		U			(2-5)
1302.5	0.6	3,4 ⁻	1304.9		1303.5	0.4		3,4 ⁻
1321.0	1.5	3,4 ⁻	1323.2		1322.5	0.4		3,4 ⁻
1326.0	2.2	5 ⁻			U			5 ⁻
1350.5	0.9	3,4			U			3,4
1360.4	0.8	5 ⁻			U			5 ⁻
1371.1	0.5	3,4 ⁻			1371.3	0.5		3,4 ⁻
1377.3	1.4	3,4 ⁻			1376.8	0.5		3,4 ⁻
1389.0	0.5	3,4 ⁻			1388.4	0.4		3,4 ⁻
1393.4	0.9	3,4 ⁻			1393.9	0.4		3,4 ⁻
1416.7	1.5	3,4 ⁻			1416.4	0.4		3,4 ⁻
1445.1	1.6	3,4 ⁻			1446.0	0.5		3,4 ⁻
1452.2	3.0	3,4 ⁻						3,4 ⁻
1471.9	0.7	3,4 ⁻						3,4 ⁻
1479.7	0.5	3,4 ⁻						3,4 ⁻
1490.4	1.5	3,4 ⁻						3,4 ⁻
1496.4	0.5	3,4 ⁻						3,4 ⁻
1527.1	0.5	3,4 ⁻						3,4 ⁻
1536.1	1.5	3,4,5						3,4,5
1541.7	0.6	3,4 ⁻						3,4 ⁻
1545.6	2.3	2 ⁻						2 ⁻
1551.6	0.5	5 ⁻						5 ⁻
1555.7	0.8	5 ⁻						5 ⁻
1570.8	1.2	2 ⁻						2 ⁻
1577.2	0.8	3,4 ⁻						3,4 ⁻
1582.3	0.6	3,4 ⁻						3,4 ⁻
1604.9	1.7	3,4 ⁻						3,4 ⁻

TABLE II (Cont.)

LEVELS IN ^{182}La

Present results			Wasson <u>et al.</u> ^a		Helmer <u>et al.</u> ^b			Recommended
E_x	ΔE	J^π	E_x	J^π	E_x	ΔE	J^π	J^π
1612.0	0.8	3,4 ⁻						3,4 ⁻
1617.5	2.5	3,4 ⁻						3,4 ⁻
1628.3	0.8	3,4 ⁻						3,4 ⁻
1635.6	0.8	3,4 ⁻						3,4 ⁻
1641.8	1.5	3,4 ⁻						3,4 ⁻
1646.1	2.0	(2-5)						(2-5)
1650.5	2.7	5 ⁻						5 ⁻
1657.6	0.6	2 ⁻						2 ⁻
1661.7	0.6	3,4,5						3,4,5
1667.0	1.5	(2-5)						(2-5)
1674.3	0.6	3,4 ⁻						3,4 ⁻
1679.6	0.5	3,4 ⁻						3,4 ⁻
1695.4	0.5	3,4 ⁻						3,4 ⁻
1701.1	1.5	3,4 ⁻						3,4 ⁻
1711.6	1.2	3,4 ⁻						3,4 ⁻
1724.7	0.9	3,4 ⁻						3,4 ⁻
1734.1	0.9	3,4						3,4
1746.5	0.9	3,4 ⁻						3,4 ⁻
1756.3	1.4	5 ⁻						5 ⁻
1762.5	1.2	5 ⁻						5 ⁻
1765.9	1.9	(2-5)						(2-5)
1769.6	1.0	3,4 ⁻						3,4 ⁻
1778.3	1.2	3,4 ⁻						3,4 ⁻

TABLE II (Cont.)

- a. Reference 15. High resolution resonance capture with the Brookhaven chopper.
- b. Reference 16. Decay of ^{182}Hf , ^{182m}Ta , thermal capture and 2 keV capture.
- c. U designates an unobserved transition.
- d. There is probably an unresolved positive parity state at this excitation.
- e. This level was observed in (d,p). The energies have been adjusted by Helmer, et al. to correspond to their energy scale.
- f. Helmer, et al. regard the existence of this level to be questionable.
- g. Helmer et al. see possible splitting of this level.
- h. The level at 662.8 seen in the averaged spectra probably contributes to this level.
- i. Helmer et al. see $E = 1000.4 \pm .5$ in thermal.
- * Seen only in averaged spectra.
- ** Parity assignment from averaged spectra.
- *** An underlined J^π indicates the most probable value.

TABLE III AVERAGED INTENSITIES (Photons/MeV/1000 Captures)

E_x (keV)	E_y (keV)	I_0^+	$\langle I(E_n) \rangle^{++}$				
			$E_n=20-100\text{eV}$	100-200	300-400	400-1000	1000-3000
50	6.01	168	226	74	108	89	80
150	5.91	72	61	102	89	66	71
250	5.81	56	55	46 [*] (69)	42 [*] (63)	73	**
350	5.71	14	16	57 [*] (114)	44	19 [*] (38)	30 [*] (60)
450	5.61	44	35	55	41	59	15 [*] (30)
550	5.51	52	68	46	66	56	26 [*] (52)
650	5.41	103	83	110 [*] (220)	68 [*] (91)	89 [*] (118)	56 [*] (112)
750	5.31	88	101	86	99	77	59 [*] (79)
850	5.21	100	104	74 [*] (89)	109	122 [*] (146)	**
950	5.11	74	88	**	**	**	**
1050	5.01	96	86	97	100	121	48 [*] (92)
1150	4.91	79	98	111	**	63 [*] (110)	**
1250	4.81	135	131 [*] (183)	81 [*] (195)	104 [*] (146)	**	**
1350	4.71	167	146 [*] (167)	170 [*] (272)	104 [*] (166)	81 [*] (162)	**
1450	4.61	142	138 [*] (161)	**	**	**	118 [*] (156)
1550	4.51	124	108 [*] (216)	104 [*] (208)	**	**	**
1650	4.41	160	**	**	**	**	**
1740	4.32	140	**	**	**	**	**

† Average intensity for 19 resolved resonances.

†† Average intensity for spectra summed over indicated neutron energy range.

* Up to 5% of E1 transitions are unobserved in this interval. Quantity in () is value adjusted for unobserved transitions.

** More than 50% of transitions are unobserved.

TABLE IV EL STRENGTH FUNCTIONS (10^{-7} MeV^{-3})

E_x	E_γ	S_0^+	$\langle S_{\text{Res}} \rangle^{++}$	$\langle S(E_\gamma) \rangle^{+++}$				
				$E_n=20-100 \text{ eV}$	100-200	200-400	400-600	600-800
50	6.01	$2.58 \pm .59$	3.60	4.34	1.42	2.07	1.71	1.54
150	5.91	$1.42 \pm .37$	1.45	1.23	2.05	1.39	1.33	1.43
250	5.81	$1.17 \pm .31$	0.79	0.78	$0.65^a(1.0)$	$0.59^a(0.9)$	1.03	aa
350	5.71		0.60	0.71	$2.55^a(5.1)$	2.00	$0.85^a(1.7)$	$1.3^a(2.5)$
450	5.61	$1.11 \pm .30$	1.04	0.83	1.30	0.97	1.39	$0.61^a(1.2)$
550	5.51	$0.93 \pm .21$	1.30	1.69	1.14	1.64	2.39	$0.65^a(1.3)$
650	5.41	$1.44 \pm .27$	1.36	1.09	$1.44^a(2.9)$	$0.89^a(1.2)$	$1.17^a(1.5)$	$0.74^a(1.5)$
750	5.31	$1.49 \pm .30$	1.22	1.41	1.20	1.38	1.07	$0.82^a(1.1)$
850	5.21	$1.06 \pm .17$	1.18	1.22	$0.87^a(1.0)$	1.28	$1.44^a(1.7)$	aa
950	5.11	$1.16 \pm .24$	1.17	aa	aa	aa	aa	aa
1050	5.01	$1.77 \pm .21$	1.69	1.52	1.71	1.76	2.12	$0.84^a(1.7)$
1150	4.91	$1.07 \pm .22$	0.85	1.05	1.19	aa	$0.67^a(1.3)$	aa
1250	4.81	$1.00 \pm .15$	1.79	$1.74^a(2.4)$	$1.08^a(1.3)$	$1.38^a(1.9)$	aa	aa
1350	4.71	$1.63 \pm .21$	1.77	$1.55^a(1.8)$	$1.81^a(1.9)$	$1.10^a(1.8)$	$0.85^a(1.72)$	aa
1450	4.61	$1.31 \pm .17$	1.85	$1.79^a(2.1)$	aa	$0.82^a(1.5)$	aa	$1.55^a(2.1)$
1550	4.51	$1.66 \pm .24$	1.51	$1.31^a(2.6)$	$1.26^a(2.5)$	aa	aa	aa
1650	4.41	$1.33 \pm .14$	1.51	aa	aa	aa	aa	aa
1740	4.31	$1.29 \pm .16$	1.21	aa	aa	aa	aa	aa

† Calculated from resolved El transitions between states of known J^π .

†† Calculated from summed intensities from 19 resolved resonances using eq. (23).

††† Calculated from summed intensities from spectra summed over indicated neutron energy range using eq. (23).

* Up to 50% of El transitions are unobserved in this interval. Quantity in () is value adjusted for unobserved transitions

Figure Captions.

1. Livermore 100-MeV linear accelerator below-ground time-of-flight facility.
2. Time-of-flight and energy resolution vs. neutron energy for the two sets of time channel widths used in this experiment. Note broken scale for the resolution curves. The discontinuities are due to changes in time channel widths.
3. Typical spectra as a function of neutron energy for γ -ray events depositing between 2.4 and 6.1 MeV in the three-crystal spectrometer.
4. Schematic level diagram for ^{182}Ta .
5. Linear absorption coefficients for γ -rays incident on germanium.
6. Schematic response of 2500-keV monoenergetic photons incident on a 17.6 cc Ge(Li) diode.
7. Typical resolution curves for a Ge(Li) diode with a room-temperature FET preamplifier as a function of γ -ray energy and detector capacitance.
8. Mountings of the a) 17.6 cc and b) 14.3 cc Ge(Li) crystals used in the three-crystal spectrometer.
9. Three-crystal spectrometer assembly showing the relative positions of the Ge(Li) diode, NaI scintillators, shielding, and sample.
10. Efficiency calibration for the 17.6 cc Ge(Li) diode. The upper curve gives the parameter ϵ_0 , defined in the text, for the full-energy and three-crystal efficiencies. The bottom graph gives the effective interaction depth, R_0 .

11. Efficiency calibration for the 14.3 cc Ge(Li) diode. The upper curve gives the parameter ϵ_0 , defined in the text, for the full-energy and three-crystal efficiencies. The bottom graph gives the effective interaction depth, R_0 .
12. Three-crystal response functions for monoenergetic 2615- and 6142-keV photons. "Response" is defined as the fraction of the total events/keV detected at each data point.
13. Schematic block diagram of the electronics for the three-crystal spectrometer and time-of-flight system.
14. Schematic block diagram of the triple coincidence portion of the electronics.
15. Overload recovery circuit developed by Radeka³⁵ to sense overloads in a charge amplifier and inject a cancelling charge.
16. Overload recovery circuit used in the majority of data collection in this experiment. A pulse is injected at Q with amplitude and duration set to cancel the γ -flash.
17. Method used for determination of peak regions. The upper graph shows the data and the results of a 3*FWHM running average for the first, second, third, and last cycles. After each cycle the data are compared with the average and a flag is set if the data exceed the average by more than one standard deviation. On subsequent averages, the previously computed averaged data are used, instead of the raw data, for computation of the *running* average if the flag is set. The lower graph shows the flagged channels as a function of averaging cycle.
18. Schematic representation of the components in the function used to fit a peak in a Ge(Li) spectrum.

19. Typical fit produced by the multiple-peak fitting routine.
20. Plot of the non-linearity (deviation in channels of a linear fit to the γ -ray energy vs. channel calibration) of the three-crystal spectrometer.
21. Sample pulse-height spectra for the three-crystal spectrometer for the 4.28-eV resonance and the neutron energy regions, 20 to 100 eV and 100 to 200 eV. The ground state transitions are indicated. The energy calibration is 2.29 keV/channel.
22. The distribution of El partial radiation widths observed in this experiment. The differential distribution is plotted as a function of $X = (S/\bar{S})^{1/2}$. The maximum likelihood fit for the chisquared distribution with $\nu = 1.38$ is plotted as well as the distributions for $\nu = 1$ and 2.
23. The maximum likelihood values of the degrees of freedom for the El partial radiation widths divided into 100-keV wide bins as a function of γ -ray energy are shown.
24. The ^{182}Ta El strength function is plotted vs. γ -ray energy. The least-squares fit of $\bar{S} = aE_Y^3$ is shown by the solid line and $\bar{S} = aE_Y^5$ by the dashed line.
25. Present results for the ^{182}Ta El strength function compared with the 0.7-MeV (n, γ) results of Earle et al.,⁴² the relative measurements of Bollinger et al.,⁴³ and the tail of the El giant resonance.²
26. The parameterized three-crystal response function for photons of energy $E_Y = E_\beta + 1.022$ MeV, where E_β is the double-escape peak energy. E_L and E_U are the points where the contribution of f_L and f_U become zero. See the text for discussion of the functions.

27. The ratio of peak response to total response as a function of the double-escape peak energy, E_d . The curve is the function, α , defined in the text.
28. Typical results for unfolding $Ta(n,\gamma)$ spectra with the parameterized three-crystal response function. The results are averaged in 100-keV wide bins.
29. Results of unfolding $Ta(n,\gamma)$ spectra for neutron energy regions between 20 and 9×10^4 eV. Background has been subtracted, detector efficiency and absolute normalization applied to give absolute intensities in photons/MeV/1000 captures.
30. Comparison of the spectrum calculation of Gardner⁵⁰ with the spectral data for the 100- to 1000-eV neutron energy region. The calculation has been multiplied by 1.5 to compare shapes. See the text for discussion.

Figure 1.

Figure 2.

COUNTS/μsec - ARBITRARY UNITS

Figure 3.

Figure 4.

Figure 5.

Figure 6.

Figure 7.

Figure 8.

Figure 9.

Figure 10.

Figure 11.

Figure 12.

Figure 13.

BLOCK DIAGRAM FOR TRIPLE COINCIDENCE
PORTION OF ELECTRONICS

Figure 14.

Figure 15.

Figure 16.

Figure 17.

Figure 18.

Figure 19.

Figure 20.

Figure 21.

Figure 22.

Figure 23.

Figure 24.

Figure 25.

Figure 26.

Figure 27.

Figure 28.

Figure 29.

Figure 30.