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SURVEY OF eV AND keV NEUTRON REACTIONS†

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I. Introduction

a. Compound Nucleus Model

The early discovery of narrow resonances in heavy nuclides using low-energ neutrons implied that a complicated process was involved, consistent with the Bohr model of the compound nucleus. In this model the neutron interacts stror with the other nucleons in the nucleus and quickly shares its energy (neutron separation energy plus kinetic energy) with them. For such a complicated moti only a statistical investigation is possible such as the distributions of reso nance parameters about their means, and the variation of their means as a func tion of mass number or neutron energy. It is only for the very lightest nucli that it is possible to consider the neutron cross sections of energetically po sible reactions from dynamic nuclear models.

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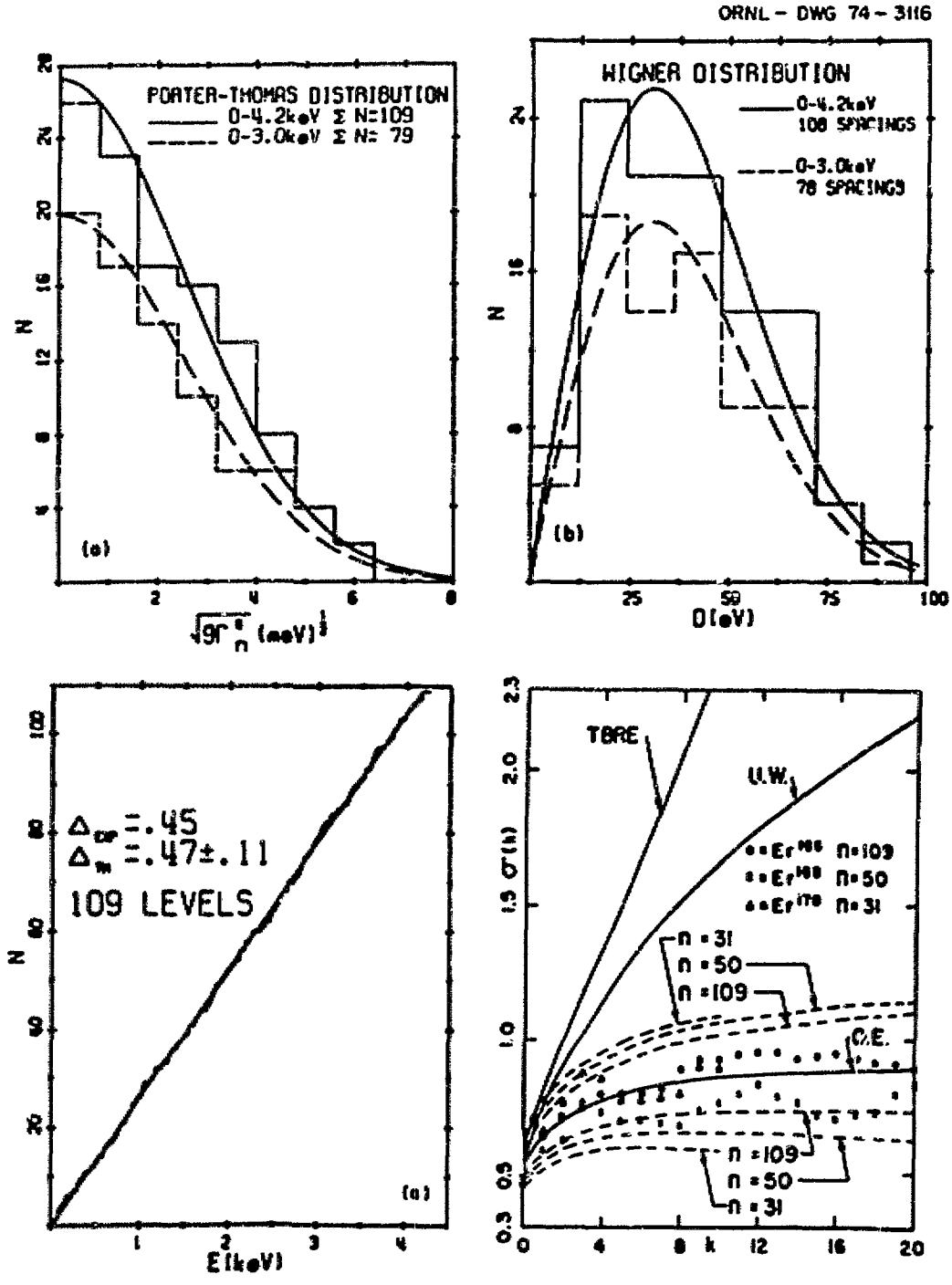

Figure 1. Statistical Distributions for ^{166}Er from Ref. 3. σ(K) is std. dev. of S(K), where S(K) is the spacing of K levels.

final states (such as for $^{238}U(n,E_{\gamma}^{(p)})$)agreed with a χ^2-distribution with $\nu = 1$; however, a detailed experiment by Wasson et al[4] has now shown this to be true. Based on the statistical model one expects that any single channel reaction will obey a $\nu = 1$ distribution. For the (n,α) reaction in the rare earth region measurements[5] indicate a $\nu \sim 1$ for individual alpha groups. I expect this work will be discussed by Soloviev later at this school. To study the fission-width distribution is difficult because two spin states are usually involved (except for subthreshold fission) and because of the $(n,\gamma f)$ process); however, for ^{239}Pu the data are qualitatively in agreement with a single channel process. In contrast from the distributions of the total radiation widths, one concludes that ~200 exit channels are involved for heavy nuclides like ^{238}U and ~20 channels for medium weight nuclides.

Level spacing information data can also be investigated for long-range order based on a test proposed by Dyson and Mehta[6] for a statistical orthogonal ensemble. Figure 1(c) shows a plot for ^{166}Er and the excellent agreement for this Δ-statistic test. An alternate presentation of the excellent agreement for ^{166}Er with the orthogonal ensemble (O.E.) but poor agreement with an uncorrelated Wigner spacing distribution (U.W.) and early calculations of Wong and French,[7] and Bohigas et al[8] two-body random Hamiltonian ensembles (TBRE) are shown in Figure 1(d). Although additional nuclides such as ^{238}U and ^{232}Th[9] give similar agreement with O.E., disagreements have been claimed by other experimenters for other nuclides.[10] Recent work has lowered the TBRE calculations and they now agree with the O.E. predictions.

c. Average Properties of Resonance Parameters

The average parameter which has been the most fruitful in describing the interaction between the neutron and the average potential of the nucleus is the ratio of the neutron width to the average level spacing for s-wave neutrons and also for higher ℓ-wave neutrons. Neutron data have been analyzed to give

p-wave strength functions (usually based on assumed s-wave parameters). In fact the first evidence of what is called gross structure was observed in total cross sections by Barschall et al[11] which led to the optical model for the neutron-nucleus interaction by Feshbach, Porter and Weisskopf.[12] Recently total cross section measurements by Camarda[13] do not result in any splitting of the strong peak in the p-wave strength function at mass 100 (arising from the spin-orbit interaction) as found by earlier experimenters.

There are several other average parameters which are of interest; namely, radiative strength functions for E-1 and M-1 transitions, fission strength functions and of course the average level spacing. Based upon Weisskopf estimates for the various gamma-ray multipolarities, Bartholomew[14] has predicted the strengths and dependence of radiation widths upon gamma-ray energy and level spacing. Bollinger et al[15] have reported that E-1 transitions vary as $\sim E^5$ (rather than E^3) which is due to the tail of the giant dipole resonance. Several claims[16] have been made of enhanced M-1 transitions at excitations $\sim$8 MeV arising from a giant M-1 resonance. Much of this evidence comes from (γ,n) threshold photoneutron measurements, but neutron measurements are invaluable in determining the parities of the states and, hence, whether an E-1 or M-1 transition is involved.

d. Non-Statistical Effects, Intermediate Structure and Doorway States

Although a great deal of eV and keV neutron data are consistent with the prediction of the statistical model systematic deviations have been detected. In some cases only small deviations are observed and they are difficult to establish firmly; however, for some processes, such as subthreshold fission, it is very dramatic. One might search for deviations of the distributions of parameters from predictions as presented in Figure 1; however, exceedingly good data would be required before any claimed deviation would be considered statistically significant. The deviations from statistical model predictions which

are observed usually manifest themselves in the dependence of a partial or the total cross section, or a specific exit channel as a function of neutron energy. Deviations are observed over energy ranges which are obviously larger than the fine-structure of the compound nucleus (eV to tens of eV), but much smaller than that of the gross structure of the optical model (a few MeV). Hence, the obvious name "intermediate" structure was coined. Since the Porter-Thomas and Wigner distributions are quite broad, one must make a careful analysis to show that an apparent intermediate structure is not simply due to random statistical fluctuations. In fact many theoreticians have devised explanations for reported phenomena which are later shown not to be statistically significant.

One mechanism which can give rise to intermediate structure is that of the doorway state concept.[17] Doorway states are simple modes of excitation such as two-particle, one-hole states which provide the mechanism that allows the single-particle system (neutron and target nucleus) to pass through more complicated configurations such as three-particle, two-hole states to lead to the final compound nucleus states. To be observable as intermediate structure the widths of these doorway states must be smaller than their spacing (∿100 keV for two-particle, one-hole states). The group of s-wave resonances in ^{206}Pb from 200 to 650 keV and the 500 keV s-wave resonance in ^{208}Pb are perhaps the best examples of doorway states.[18] However, the doorway state in this particular example is more likely to proceed via a particle-vibration configuration[19] than a 2-particle, 1-hole configuration.

The most striking example of intermediate structure induced by neutrons is that of subthreshold fission discovered in ^{237}Np, ^{240}Pu and ^{241}Am in 1967. Clusters consisting of several fine-structure fission resonances are well separated from each other by ∿100 eV. This startling phenomenon can be explained readily in terms of the double-humped fission barrier expected from a nuclear model for these heavy nuclides proposed by Strutinsky.[20] Non-statistical effects have

also been observed in the neutron capture process. These include direct or potential capture, channel or valency capture,[21] and a semi-direct process involving doorway statessuch as 2-particle, 1-hole states. The existence of a M-1 giant resonance[16] in the photoneutron reaction (the inverse reaction of neutron induced ground state gamma ray transitions) can also be considered intermediate structure although its width may be hundreds of keV wide.

Also correlations between partial widths of different channels must be considered a departure from the pure compound nucleus model. A correlation between two channels is equivalent to a direct cross section between them. Strong correlations have been observed between gamma ray strengths from thermal neutron capture and spectroscopic factors from (d,p) reactions in the mass-range 40 to 70. The correlation is enhanced for some nuclides when the power k representing the energy dependence of the gamma rays (E^k) is reduced from a value of 3 expected for E1 radiation. Although correlations between (d,p) and resonance neutron capture have been reported, the evidence is not conclusive in many cases. Strong correlations have been observed between neutron widths of p-wave resonances in ^{92}Mo and ^{98}Mo and the strengths of electric-dipole transitions arising from valency capture. The strengths of ground-state E1 transitions can also be obtained from threshold photoneutron measurements, and data on ^{91}Zr[22] and ^{29}Si show strong correlations between neutron widths and ground-state E1 transitions. Also correlations have been reported between neutron and radiation widths in the mass range 50 to 60; this correlation may arise from a few strong high energy gamma rays. A correlation between partial widths may indicate the existence of a doorway state such as for ^{28}Si, but in general doorway states are different from channel to channel and only rarely will a doorway state be prominent in several channels.

Finally, very exotic periodicities in the spacings of neutron resonances have been reported by several physicists.[23] Several medium and heavy nuclides show

a marked preference for resonances to be separated by common equispaced intervals. These unusual non statistical effects which are apparently statistically significant have not been explained.

II. Experimental Techniques, Measurements and Analysis

a. Time-of-Flight Technique

Monoenergetic neutrons ($\Delta E/E \lesssim .01$) can be obtained from a nuclear reactor for neutrons up to ∿10 eV and from a thin Li or T target and a MeV charged-particle accelerator for neutrons above ∿50 keV. Between these two neutron energies the time-of-flight technique must be used to obtain high resolution neutron cross section data. Also except for a few particular experiments such as nuclear inelastic scattering for MeV neutrons, the time-of-flight technique is superior even up to neutron energies of several MeV. The important characteristic of the neutron source is an intense, short-duration pulse of neutrons with an appropriate average neutron energy. This neutron pulse may be produced by a pulsed electron accelerator (∿100 MeV), a proton or deuteron cyclotron (50-500 MeV), a pulsed reactor, a combination of an accelerator plus booster (or pulsed reactor), or even a nuclear explosion. The narrowness of the neutron pulse desired depends mainly upon the neutron energy range to be investigated and to a lesser extent upon the type of measurement to be made. For example, the ∿.2-μsec pulses from an accelerator plus booster do not contribute appreciably to the resolution below ∿100 eV neutron energy. From a few keV to several hundred keV pulse widths from ∿30 to ∿3 nsec are desired and above ∿1 MeV $\lesssim$1 nsec are required for ultimate resolution. Obviously the peak neutron intensities for these pulse widths and backgrounds are important in comparing the merits of the various sources. I shall briefly describe our facility at ORNL which was used to obtain most of the data presented in this paper.

The pulsed neutron source at ORNL consists of a linear accelerator[24] which can produce pulses of ∿25 amperes (peak) of 150-MeV electrons with widths from

$\sim$3 to 30 nsec and repetition rates up to 1000 pps. Neutrons are produced with a peak intensity of $\sim 6 \times 10^{18}$ neutrons/sec in a small water-cooled laminated Ta-target capable of dissipating 55 kW of power. The evaporation neutrons with an average energy of $\sim$1 MeV are moderated by a 3 cm thick, 15 cm diameter C-shaped water moderator around the target producing a neutron spectrum of $1/E^{.78}$. Moderated neutrons are captured in the water producing a background of 2.23 MeV gamma rays. Detectors are shielded from direct gamma rays from the tantalum by a shadow bar. The moderated neutrons are permitted to travel down 11 different flight paths with stations located 10 to 200 meters from the target. The neutron energy is computed from the distance and the neutron flight time. Figure 2 is a schematic of the ORNL facility called ORELA. The characteristics of the accelerator (3 to 30 nsec) were chosen to optimize measurements in the neutron energy region from 3 to 300 keV. However, excellent measurements have been made below 3 keV to a few eV, and above 300 keV to several MeV. Below $\sim$5 keV the neutron energy resolution is determined by the uncertainties in the flight path due to source and detector, while above $\sim$500 keV the resolution is determined by the pulse width. Depending on the experiment, which dictates the flight distance, energy resolutions $\Delta E/E$ from 0.01 to .0005 are realized.

b. Detector Systems at ORELA

Neutrons can be detected by one of a various member of detectors, depending on the type of experiment, which are placed at the ends of the flight paths. A total cross section or transmission measurement requires an efficient, fast neutron detector with low background. For neutrons from a few eV to $\sim$50 keV a ^{6}Li glass scintillator 11.4 mm Dia., 1.27 cm thick mounted on a RCA 4522 5" Dia. phototube is used. For neutrons from $\sim$20 keV to $\sim$2000 keV a NE-110 plastic scintillator[25] mounted on a RCA 4522 phototube is used. Plastic scintillators have been used for years for neutrons $\gtrsim$ 200 keV, but never before for keV neutrons. Figure 3 shows the efficiency of the ^{6}Li glass scintillator, of three different NE-110 detectors and a standard plastic scintillator (Naton 136). For

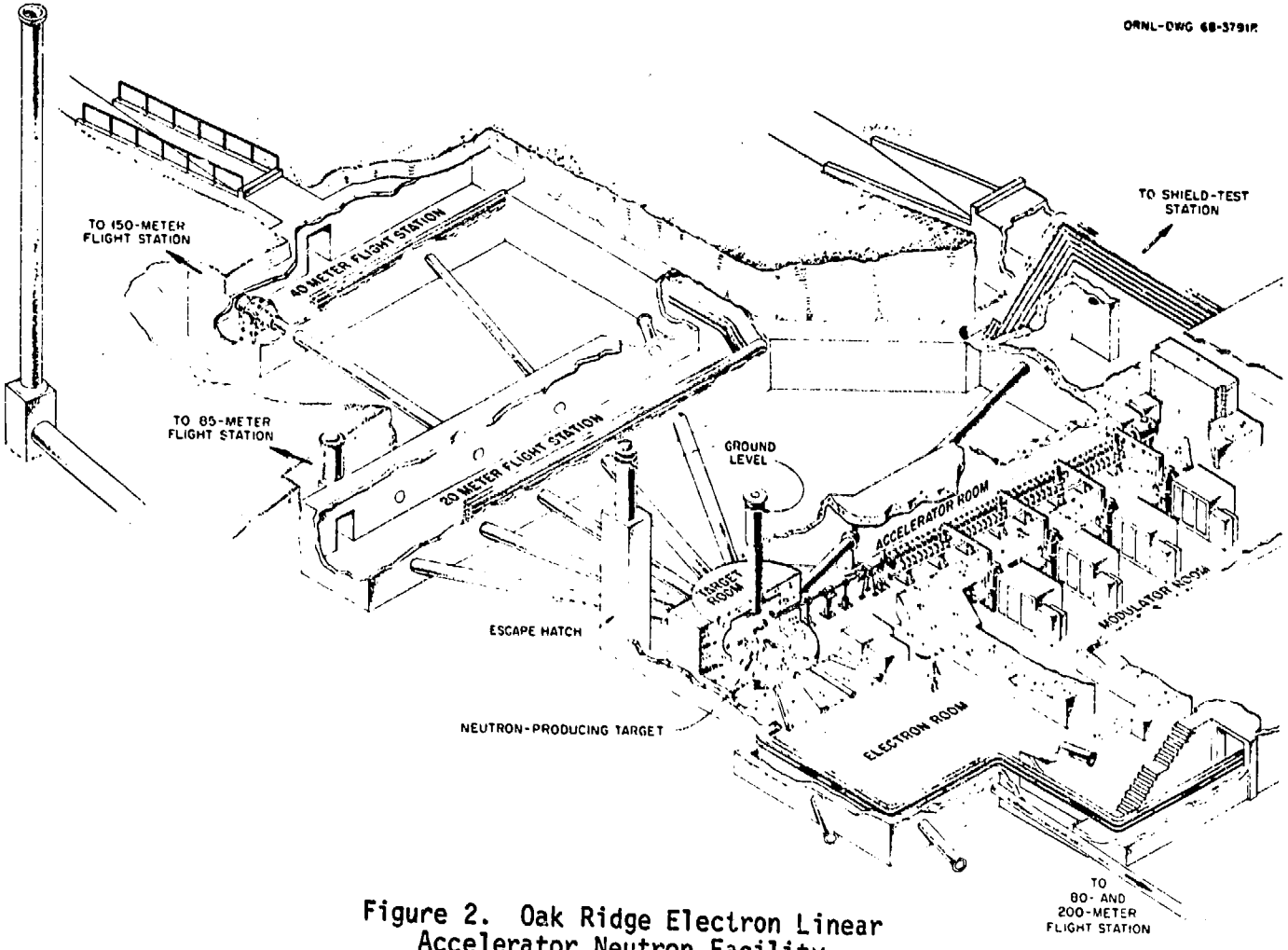

Figure 2. Oak Ridge Electron Linear Accelerator Neutron Facility.

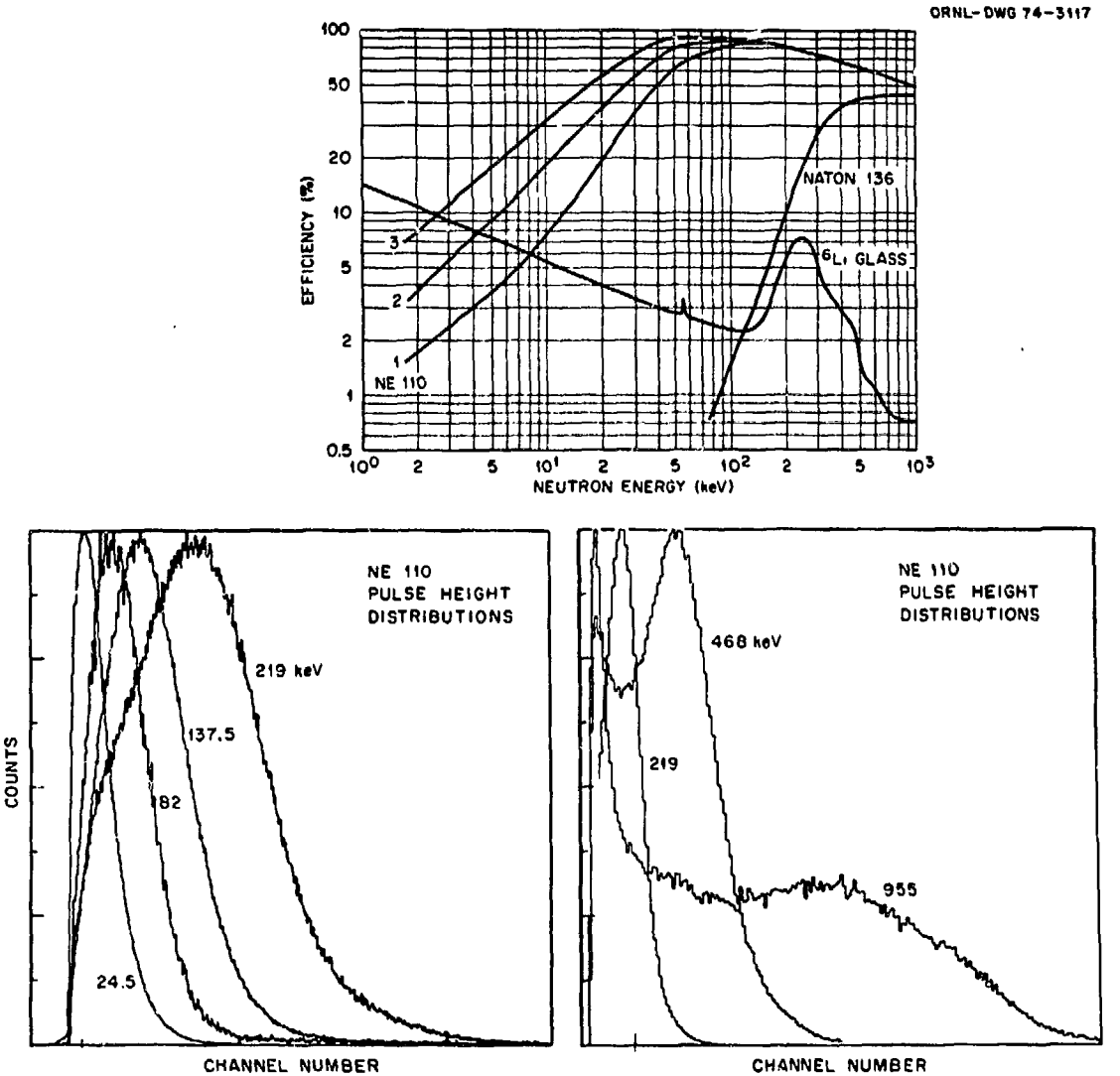

Figure 3. Efficiency and Pulse Height Distributions of NE-110.

the energy region from ∿10 to 300 keV, this NE-110 has a high efficiency approximately 10 times that of the ^{6}Li detector. The lower half of Figure 3 shows pulse height distributions from it for different monoenergetic groups of neutrons from Fe windows. By using pulse height windows particular neutron energy regions can be emphasized and backgrounds due to gamma rays and other energy neutrons can be reduced.

For capture cross section measurements at ORELA two different detectors are used. One is a large cylindrical liquid scintillator[26] 1.56 m Dia. and 2.2 m long with a ∿15 cm Dia. tube passing through the axis. A neutron beam is collimated to pass through the tube and the samples to be measured are placed in the center of the tube. An efficiency of 50 to 90% for detecting gamma rays is achieved and a time resolution of ∿6 nsec is possible. The other detector[27] used at ORELA for capture cross section measurements of small samples of enriched stable isotopes is a generalization of the Moxon-Rae approach. By using a "total energy weighting technique", gamma ray efficiencies of ∿15% per neutron capture are realized. The nonhydrogenous liquid scintillators are insensitive to neutrons and a time resolution of < 2 nsec is obtained.

To measure fission cross sections several different fission detectors have been used at ORELA. For the subthreshold fission measurements of ^{234}U a multiplate ionization chamber containing 181 mg ^{234}U was used. With a spacing between plates of 3 mm, 19 cm pressure of methane gas and a voltage between plates of 90 volts, a time resolution of < 2 nsec was achieved. For measurements of σ_F for ^{249}Cf (352-year half life) thin (125 μm) diffused junction Si fragment detectors directly in the neutron beam close to the fissile sample were used. With only 128 μgm of sample, the alpha count rate was ∿10^7/sec and a current sensitive preamplifier with fast rise and fall times (3 and 15 nsec) was essential to avoid alpha pileup. For the subthreshold fission measurements of ^{240}Pu fast neutrons were detected using a fast plastic scintillator with pulse shape discrimination to distinguish fission pulses from gamma ray pulses from capture.

With this technique both the fission and capture cross sections are measured simultaneously.

For measurements of the energies of gamma rays from neutron capture in individual resonances, a large volume Ge(Li) detector is used. A Faraday shield surrounds the detector system at the flight station, and the analog pulse is digitized at the computer 300 feet away. It is transmitted to the digitizer via a 93 ohm twin-ax cable to cancel common mode noise. An overall gamma-ray resolution of $\lesssim$ 0.1% for high energy gamma rays is achieved. Gamma rays from neutron capture for resonances up to $\sim$30 keV have been studied. In addition to resonance capture, this GeLi detector is valuable in investigating the yield of gamma rays from nuclear inelastic scattering up to several MeV.

c. Analysis of Total, Capture and Fission Data

From high-resolution measurements parameters of hundreds of resonances in a single nuclide can be obtained. The parameters of a resonance are the resonance energy E_0, the neutron width Γ_n, the radiation width Γ_γ, the fission width Γ_F (also interference), alpha widths Γ_α^i, partial radiation widths Γ_γ^i, the orbital angular momentum of the neutron ℓ, the spin of the compound state J (or the statistical weight factor g) and inelastic scattering neutron widths $\Gamma_{n'}$. The potential scattering phase shifts can also be obtained from total and scattering cross section data. When the neutron energy resolution and the Doppler broadening are small compared to the natural widths of the resonances Γ, the total widths and often one other resonance parameter can be obtained from a single measurement based on reasonable assumptions. However, if Γ cannot be measured, only combinations of parameters are determined in a single experiment. For example, total data yields $g\Gamma_n$, capture data $g\Gamma_n\Gamma_\gamma/\Gamma$, fission $g\Gamma_n\Gamma_F/\Gamma$ and scattering $g\Gamma_n^2/\Gamma$. Hence, the fission measurement of ^{234}U must be combined with the transmission data to obtain the fission widths of the resonances. The ℓ-value of a resonance can be obtained for resonances where $\Gamma_n \gtrsim \Gamma_\gamma + \Gamma_F$ from the

interference between resonance and potential scattering observed in a transmission measurement and other reasonable assumptions.

d. Statistical Tests for Intermediate Structure

Many claims of intermediate structure have been made based on tests which indicate a non statistical behavior to a significant confidence level. In a recent paper by Baudinet-Robinet and C. Mahaux,[28] these tests were reviewed, new tests have been proposed and earlier claims of intermediate structure have been reanalyzed. Possibly the most useful tests for randomness are those relating to the concept of "runs". James[29] has proposed a test which considers the number of runs above a reference R (ideally the median) and the number below this reference. A "run above" is an unbroken series of observed quantities lying above R. Another test counts "runs up" and "runs down". The number of runs expected from random statistical data can be calculated for both tests and also the standard deviation. These two tests have been applied by James et al[30] to ^{235}U and they conclude that significant deviations occur for both the fission and capture cross sections of ^{235}U from 10 to 40 keV. Other run tests consider the longest run above the medium, and the longest run relative to the value of the optimum run length. The strengths and weaknesses of the various tests are presented in reference 28. They emphasize that it is sufficient that only one test be significant to establish intermediate structure, but some tests are rather sensitive to only one single event.

e. Averaged Resonance Capture and Beams of Filtered Neutrons

In order to investigate the nature of gamma radiation from neutron capture and the low-lying excited states of compound nuclei, neutron spectra which average over hundreds of fine structure resonances have been used by several experimenters. Bollinger at ANL has used ^{10}B shielded samples in a reactor, while other experimenters have used beams of filtered neutrons with $\Delta E/E \sim 0.2$. A thick Sc filter produces $\sim$ 2-keV neutrons, a thick Fe (+Al+S) filter 23.5-keV

neutrons and a thick Si filter ∿150 keV. We have found that a 20"-Fe filter beam at ORELA with ∿20 intense energy groups is valuable for investigating pulse shape discrimination of neutron detectors and other characteristics such as shown in Figure 3. A thick ^{238}U filter also produces many monoenergetic groups of neutrons a few eV wide up to ∿1000 eV which may be useful for solid state physics investigations.

III. Results from Total Cross Section Measurements

a. Potential Scattering of Neutrons by Calcium

The total cross section of calcium has been measured by J. L. Fowler and C.H. Johnson from 50 to 1050 keV using three sample thicknesses and a NE-110 detector located at the 200-meter flight path. Figures 4 and 5 show the cross section of calcium up to 1050 keV. The burst width was 5 nsec and the overall resolution ranges from 30 eV at 50 keV to 1 keV at 1000 keV. The cross section shows broad s-wave resonances and much narrower p, d and f-wave peaks. The data have been analyzed to obtain neutron widths, spins and parities of the resonances and the phase of the potential scattering for J = 1/2 to 7/2 as a function of neutron energy. These potential phase shifts are compared to the scattering from an energy-dependent Saxon-Woods real well with a spin-orbit term with parameters consistent with the energies of known bound states and with nucleon scattering at much higher energies. The partial wave of each resonance is identified simply by the continuity of the potential phase shifts. For example, all $p_{3/2}$ resonances have negative, and $d_{3/2}$ resonances have positive phase shifts. Two cases for J = 5/2 and 7/2 with large negative phases are anomolies because the centrifugal barrier rules out such large values for f-waves. Also the negative s-wave potential phase required for the multilevel R-function curve in Figures 4 and 5 is much smaller than predicted from the assumed real well. This may be because the absorptive spreading of the 3s state was ignored. From the magnitudes of the potential phases for the various ℓ-values, Fowler and Johnson

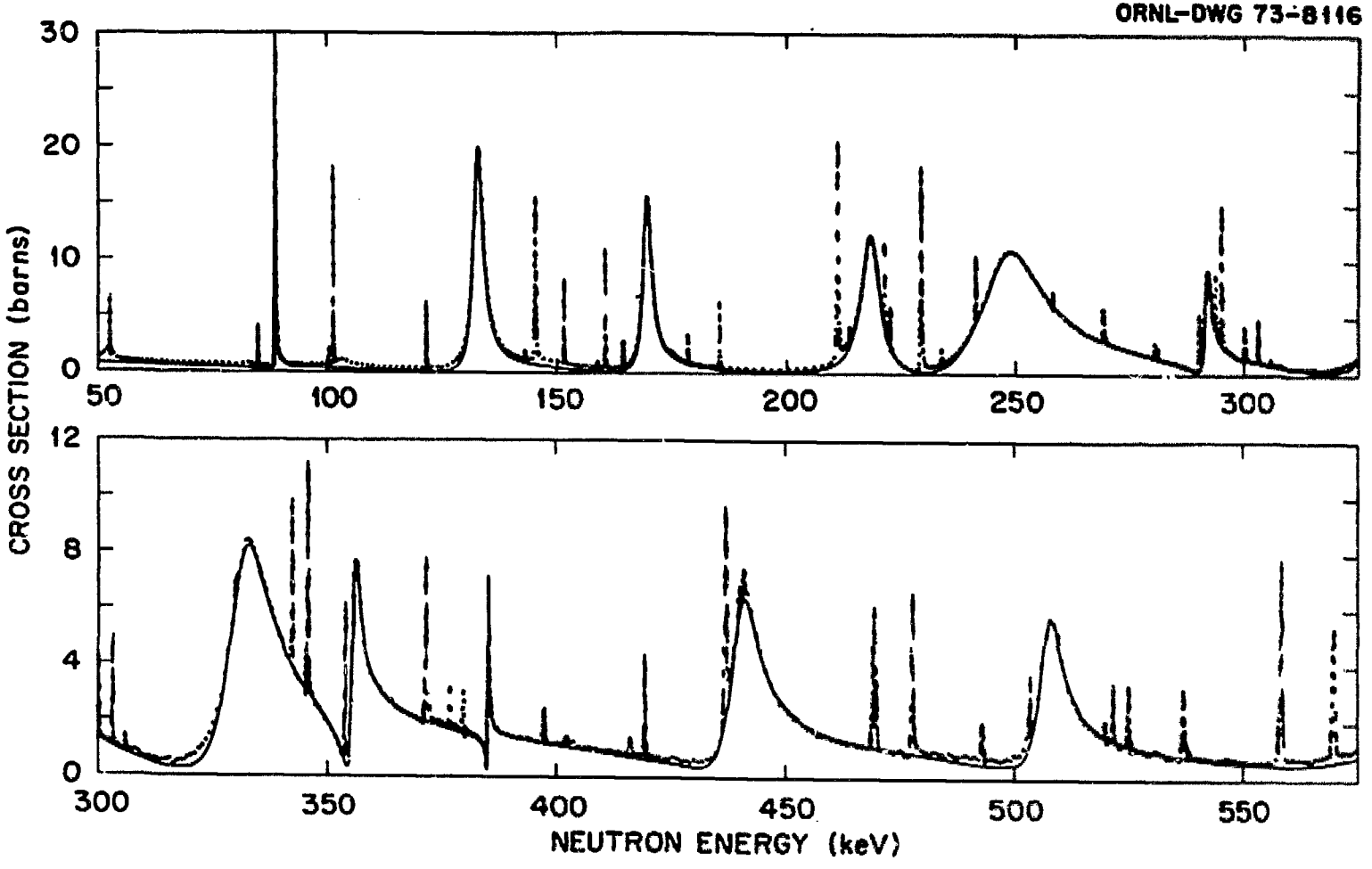

Figure 4. Total Cross Section of Ca.

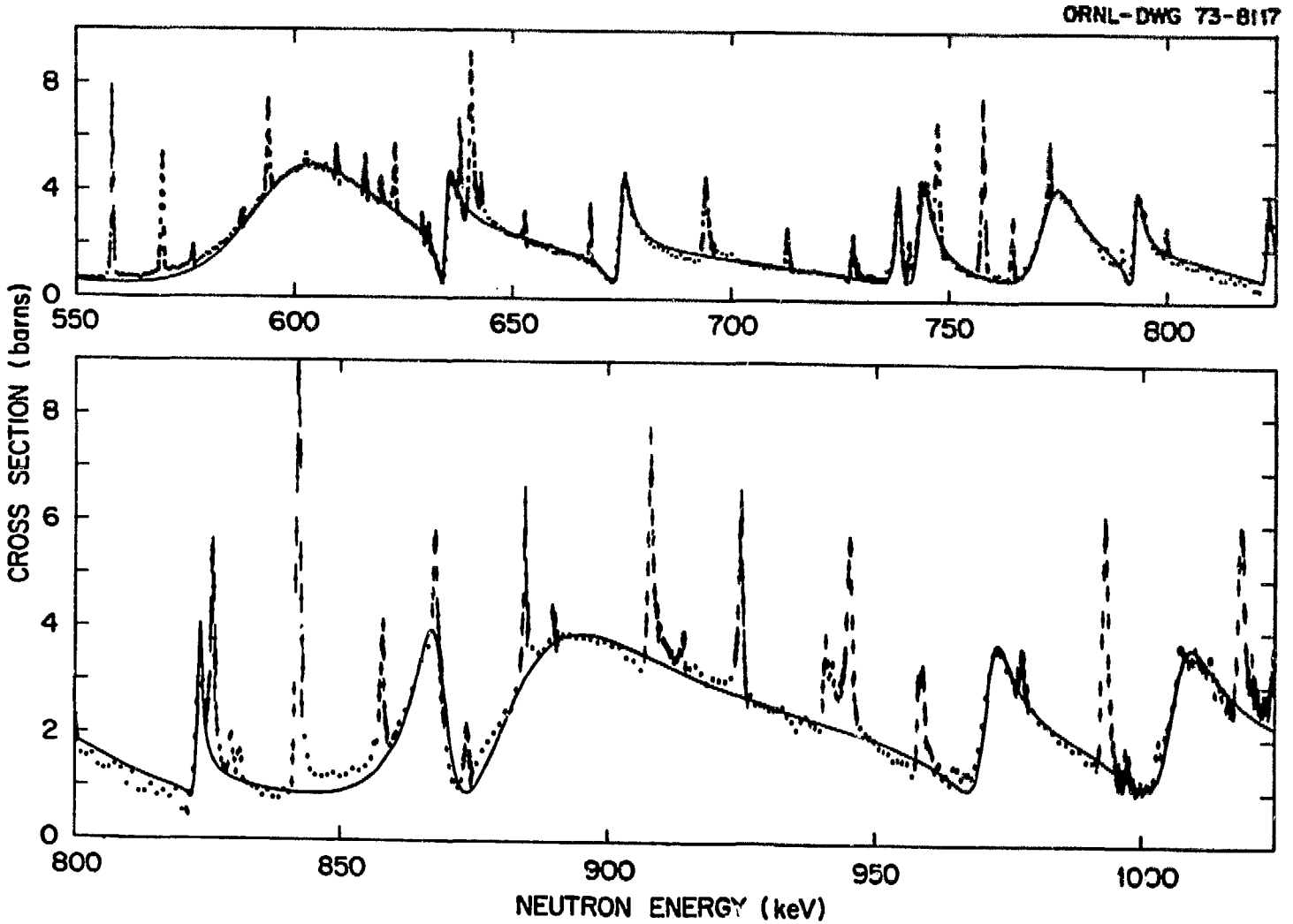

Figure 5. Total Cross Section of Ca.

hope to make appropriate adjustments in the model potential.

b. Non-existence of a Giant M1 Resonance in ^{208}Pb

Total cross section measurements were made using a 2.54 cm Dia. ^{207}Pb sample (92.4%, 253 gm, 1/N = 6.865 barns/atom) with a NE-110 detector at the 200-meter flight station. Using 5-nsec bursts an energy resolution of 0.05 to 0.1% from 20 to 1000 keV is obtained. The principal interest for this measurement was to check the spin and parity assignments for several resonances which were claimed to be 1^+ states. Based on a 1^+ assignment to seven states Bowman et al[31] reported a concentration of M1 strength in ^{208}Pb at an excitation of 7.9 MeV with a width of ∿700 keV from threshold photoneutron and angular distribution measurements on ^{208}Pb. M1 excitation to 1^+ states requires p-wave neutron emission. The M1 strength was ∿51 eV or ∿50% of the M1 strength predicted from shell-model calculations of spin-flip transitions in the $i_{13/2}$ neutron shell and $h_{11/2}$ proton shell (or 100% if polarization effects are included). Recently Toohey and Jackson[32] repeated these photoneutron measurements with better neutron energy resolution and have questioned the 1^+ assignments except for two resonances at 181- and 318-keV. They showed a small admixture of d-wave in the s-wave yield could give an asymmetric angular distribution which could be similar to that expected for p-wave neutron emission. Figure 6 shows the total cross section for the two energy regions of interest. With the improved energy resolution of these total cross section data (a factor of 20 better than used for the photoneutron data) it is obvious that the two resonances seen in the photoneutron data are each several resonances. For example, in the 181-keV energy region, there is a small s-wave resonance with spin 1^- at 181.5 keV and 2 probably p-wave resonances at 181.1 and 180.9 keV. Also in the 318-keV energy region, there is a large s-wave resonance of spin 1^-, a large p-wave of spin 2^+ and a small (possibly s-wave) resonance at 317 keV. Hence, the neutron peaks in the photoneutron reaction at 181 keV and 315 keV are probably not due to strong M1

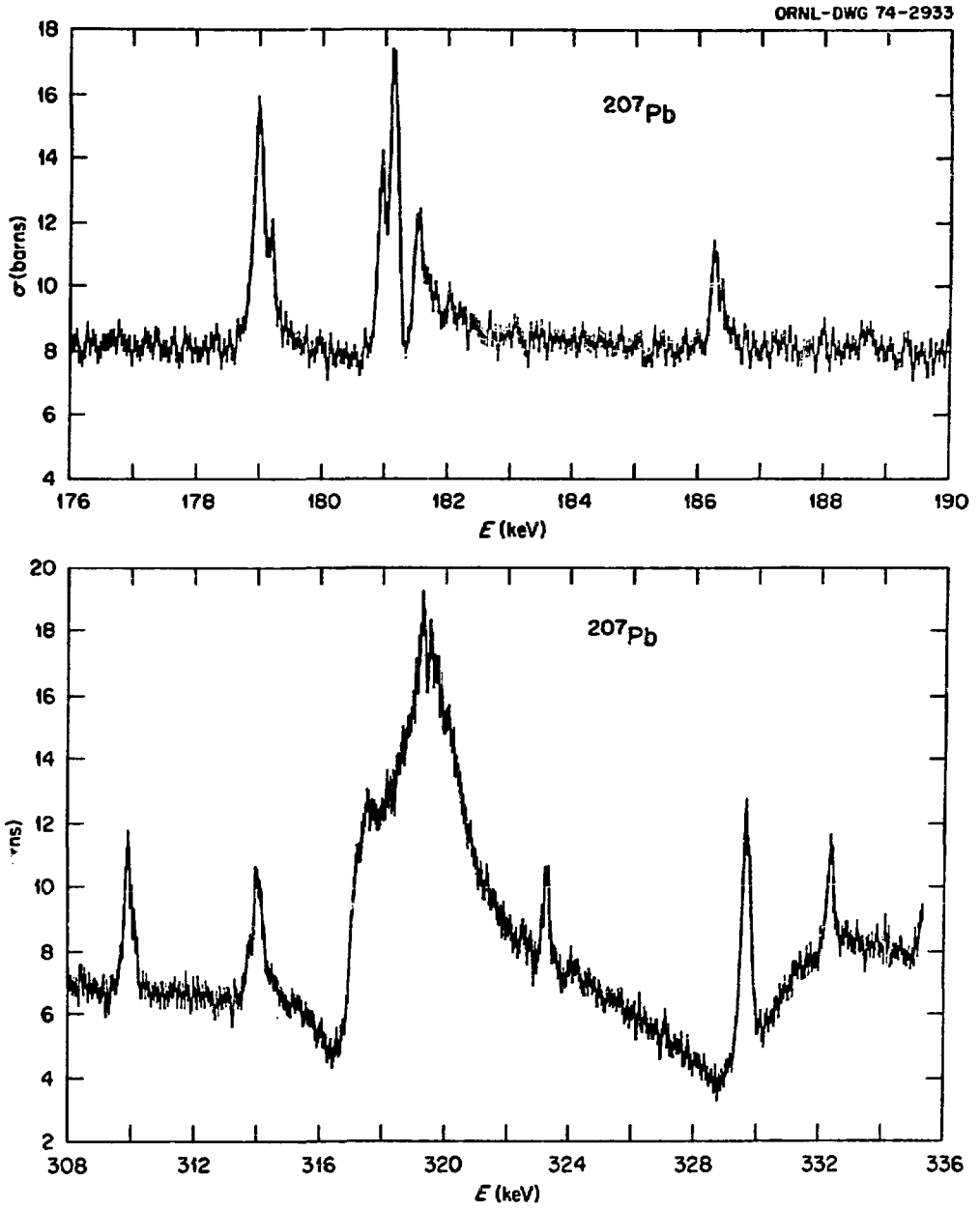

Figure 6. Total Cross Section of ^{207}Pb.

transitions but normal E1 transition to 1^- states which decay by s-wave neutron emissions. Hence, there is now no evidence of strong M1 transitions in ^{208}Pb.

c. Total Cross Section of ^{206}Pb

The total cross section of ^{206}Pb is of interest because it is perhaps the best example of a doorway state and because a giant M1 resonance has been reported in ^{207}Pb from threshold photoneutron measurements.[33] Also a strong correlation had been reported[34] between the ground-state radiation widths and the neutron widths of $1/2^+$ s-wave resonances reported by Farrell.[18] We have measured the ^{206}Pb total cross section using a 2.54-cm thick sample with a NE-110 detector at 200 meters and 5-nsec bursts. An energy resolution of 0.05 to 0.1% from 20 to 1000 keV was realized. Some of the data are shown in Figures 7 and 8. Several additional small s-wave resonances are found such as at 92.5, 146.5, 297.7, 477 and 531 keV,in addition to the previously reported eleven large s-wave resonances up to 600 keV. From the shape of these s-wave resonances the s-wave potential phase shift as a function of energy can readily be determined. In the 400-keV energy region the s-wave potential phase shift is near 90° and s-wave resonances appear as minima rather than maxima. Many p-wave and d-wave resonances are observed. It is obvious that resonances at 204, 345, 351 and 420 (which were assumed to be s-wave[33] and hence excited by E1 transitions) are not s-wave. Hence, earlier attempts to establish a correlation between the ground state widths and neutron widths for s-wave resonances are meaningless because of these misassignments and omissions. Also the case for a giant M1 resonance in ^{207}Pb needs to be reevaluated based on these high resolution total cross section data since many of the resonances are probably d-wave. A careful analysis of the total cross section, similar to that of calcium, is required to firmly establish all the assignments.

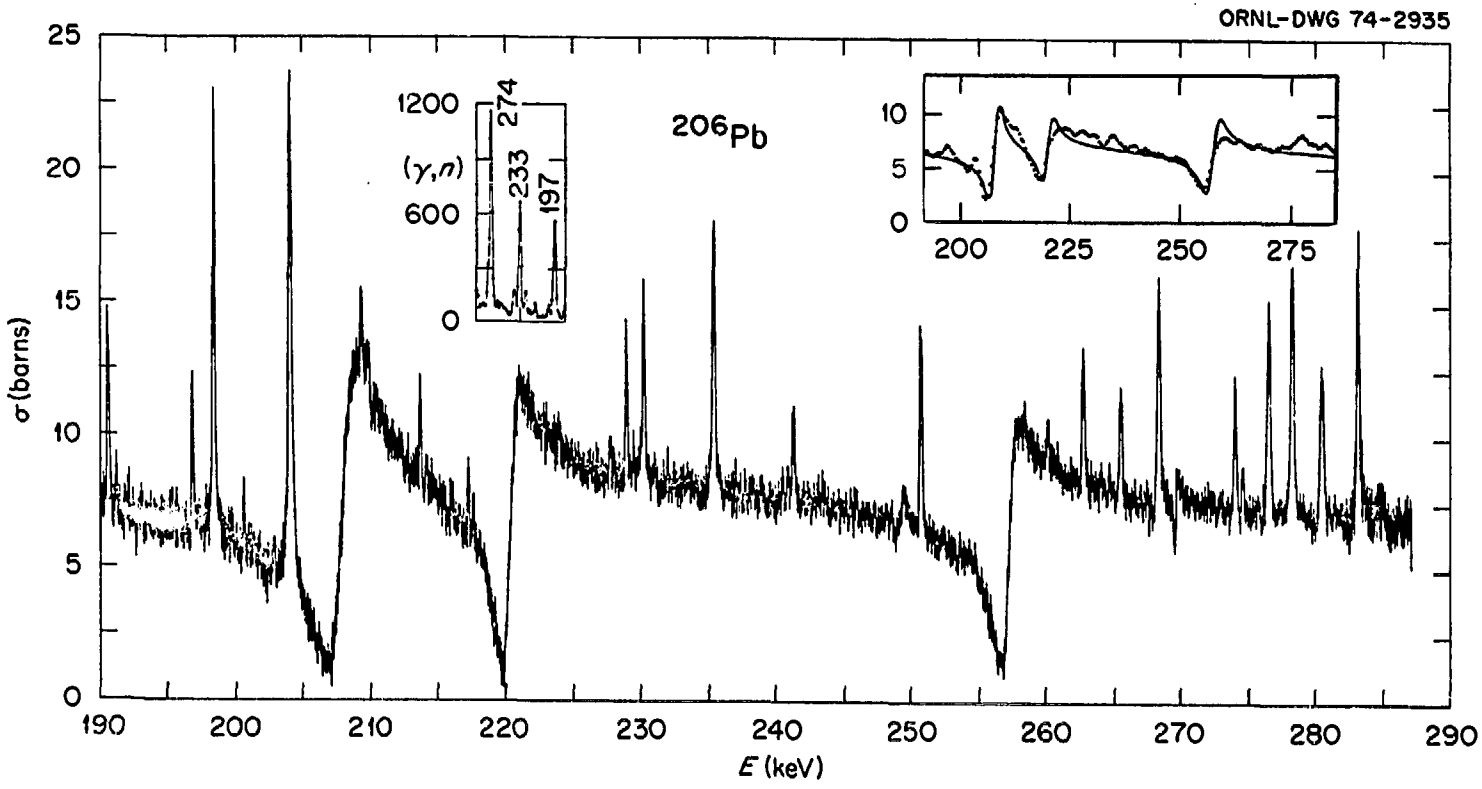

Figure 7. Total Cross Section of ^{206}Pb; inserts from Ref. 33 and Ref. 18.

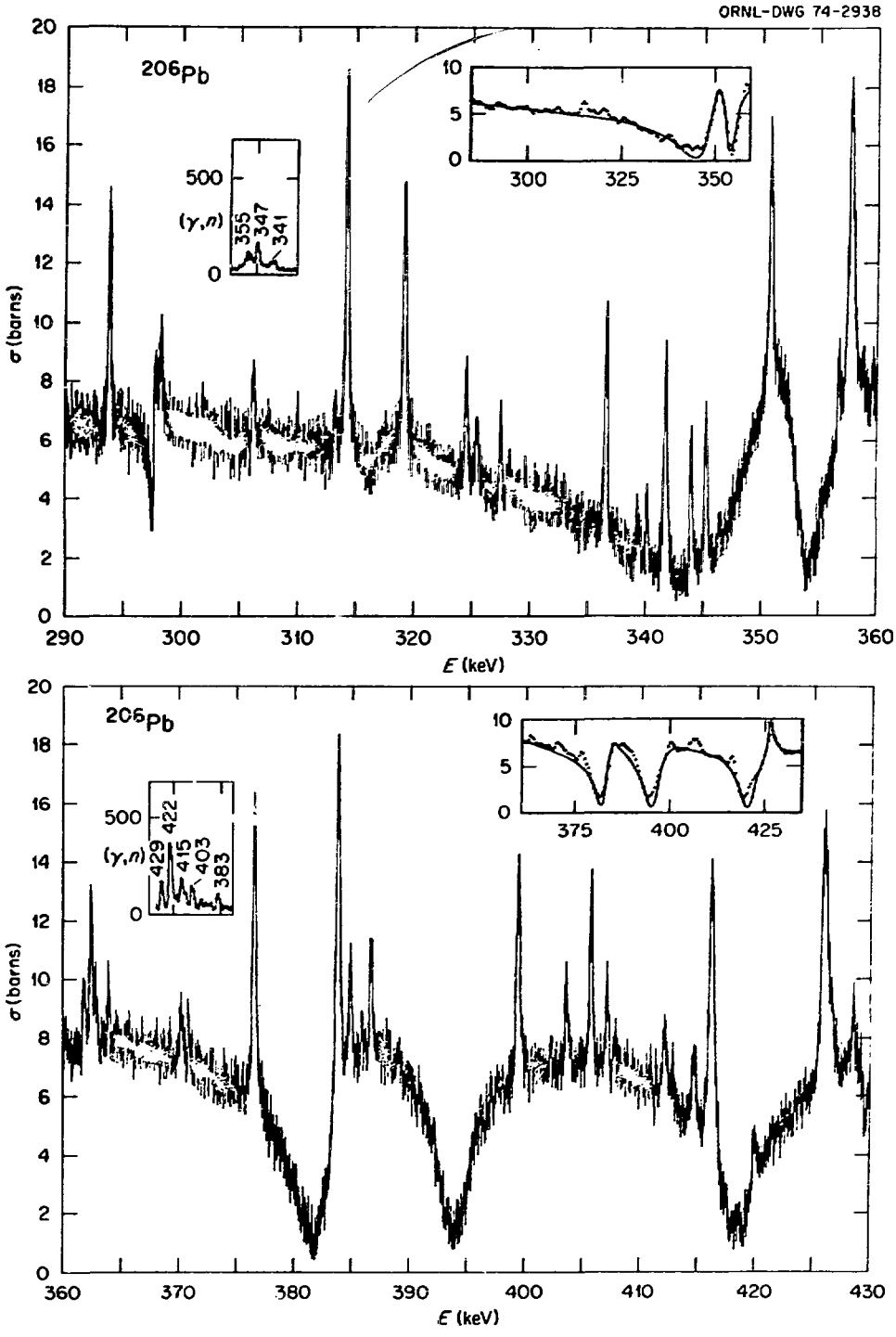

Figure 8. Total Cross Section of ^{206}Pb; inserts from Ref. 33 and Ref. 18.

d. E1 Valency Transitions from $^{91}Zr(\gamma,n_0)$ and $^{90}Zr(\sigma_T)$ Data

In order to interpret the threshold photonuclear measurements upon $^{91}Zr(J=5/2^+)$ made by Toohey and Jackson[22] high resolution total cross sections of ^{90}Zr were needed to determine the parities and reduced neutron widths of the resonances. The transmission measurements were made at ORELA using 30-nsec pulses resulting in an energy resolution ∿0.1%. The s-wave resonances were readily identified from their asymmetrical shapes and the $3/2^-$ assignments to the p-wave resonances were made from the photoneutron data. In the photoneutron measurements $1/2^+$ states and hence s-wave neutron emission are excited only by E2 radiation, while $3/2^-$ states and hence p-wave neutron emission are excited only by E1 radiation. The reduced neutron widths γ_n^2 have been computed by Toohey and compared to the ground state widths $\Gamma_{\gamma 0}$. They found a strong correlation for $J=3/2^-$ states ($\rho=0.59$) and after correction for an estimated compound nucleus contribution the correlation increased to +0.77. Such a correlation would be expected if valency capture were important since for valency capture $\Gamma_{\gamma 0} \propto \gamma_n^2$. If valency capture were responsible for the entire radiative strength the correlation would be unity. Toohey and Jackson deduced that < 40% of the ground state radiative strength is from compound nucleus formation and > 60% from valency capture. They also concluded that the neutron widths are observed to follow a Porter-Thomas distribution, while the photon widths appear to follow a χ^2 distribution with two degrees of freedom.

IV. Subthreshold and Threshold Fission

a. Double-Humped Potential for Subthreshold Fission

The intermediate structure observed in subthreshold fission can readily be explained[35] in terms of the double-humped potential proposed by Strutinsky.[20] This double-humped potential provides the possibility for the existence of two types of compound states at energies below the top of the barrier since each well has a different deformation. The states corresponding to the first well

with a deformation comparable to the permanent deformation of the nucleus in its ground state are called class-I states. Class-II states are more strongly deformed and correspond to the second well of the potential. Class-II states are more widely spaced (since the minimum of the second well is higher (∿2 MeV) than that of the first well), they have larger fission widths (because only the outer barrier needs to be penetrated), and their neutron widths are smaller because there is practically no overlap between the wave functions of class-II states and that of an outgoing neutron wave coupled to the target nucleus in its ground state. The details of subthreshold fission depend sensitively upon the relative heights of the inner and outer barriers. Basically three types of coupling between class-I and class-II states can occur as outlined by Lynn.[35]

(i) Narrow class-II states and weak coupling to class-I states. In this case class-II states are sufficiently below the tops of both the outer and the inner barriers that their fission widths for penetrating the outer barrier and their coupling widths for coupling with states in the first well are small compared to the spacing of the class-II states. This type of coupling predicts that one of the resonances (or a very few) in a cluster would have a large fission width but a small neutron width. The first cluster in ^{242}Pu,[36] ∿800 eV, and perhaps ^{240}Pu seem to be a good examples of this type of coupling.

(ii) Narrow class-II states and moderate coupling to class-I states. In this case the outer barrier is still rather high but the inner barrier is low. Hence, the fission widths of the class-II states are small but their coupling widths for coupling into the class-I states are large (but less than the spacing in the second well). However, the inner barrier must be strong enough to prevent too strong a coupling which would wash out the intermediate structure. This type of coupling predicts that the fission widths on the average will follow a Lorentzian distribution and individual fission widths should have a Porter-Thomas distribution about this Lorentzian line. The width of a fission cluster will be the

coupling width and the sum of the fission widths in the cluster will be equal to the fission width of the class-II state. The first cluster in ^{234}U at ∿650 eV reported by James et al[37] seems to demonstrate this type of coupling.

(iii) Broad class-II states and weak coupling to class-I states. In this case the inner barrier is rather high but the outer barrier is low. Hence, the class-II state is now sufficiently broad to encompass many resonances whose fission widths on the average will again follow a Lorentzian distribution and have a Porter-Thomas distribution about this Lorentzian line. The width of the cluster will be the fission width of the class-II state and the sum of the fission widths in the cluster will be equal to coupling width. Also the neutron width of the class-II state is very small and this broad state will only appear as a nearly undetectable background under the narrow fission resonances. The first cluster of ^{237}Np at ∿40 eV seems to be an example of this type of coupling. For ^{237}Np two spins are possible, 2^+ or 3^+, but all resonances in each fission cluster should contain only one spin for this picture to be correct.[38]

b. Subthreshold and Threshold Fission and Total Cross Section of ^{234}U

As mentioned earlier this nuclide seems to be a good example where the inner barrier is lower than the outer barrier. However, the earlier measurements[37] did not quite cover even the first fission cluster at ∿600 eV. Hence, high resolution fission and transmission measurements were made at ORELA by James and coworkers in order to determine the fission and neutron widths of all the resonances in the first cluster and to obtain information on class-II levels at higher neutron energies. In addition to a Lorentzian distribution one resonance in each cluster might be identified as a class-II level if it should have a large fission width and a very small neutron width. The fission measurements were made with an ionization chamber containing 181 mg of ^{234}U at a 20.14-meter flight path and a neutron energy resolution of 0.3%. The total measurements were made using a 5.69-gm sample of U_3O_8 (99.865% ^{234}U, 6.45 x 10^{-3} atoms ^{234}U/barn) cooled to

liquid nitrogen temperature to reduce the Doppler broadening. A ^{6}Li glass scintillator was located 78.203 meters from the target resulting in a neutron energy resolution of 0.08%, which is less than the Doppler broadening up to a neutron energy of ∿900 eV. A small part of the fission and total data is shown in Figure 9. Although several resonances were observed which had large fission widths and small neutron widths, no single resonance could be identified in the first cluster as the class-II level. All resonances seen in fission were observed in transmission.

The neutron and fission widths of 118 resonances observed below 1.5 keV have been derived using the area analysis program of Atta and Harvey and from the measured areas of each resonance in the fission cross section. By correcting for "missed" resonances in the transmission data on the assumption that the reduced widths follow a Porter-Thomas distribution the average level spacing in the first well D_I was computed to be 10.7 ± 0.5 eV and the s-wave strength function, $\overline{\Gamma_n^0}/D_I$, equals (0.86 ± 0.11) x 10^{-4}. The energy dependence of the fission widths is shown in Figure 10. The fission widths appear to have a Lorentzian shape, shown by the solid line which is centered at 650 eV, about which the class-I fission widths have a Porter-Thomas distribution. In estimating the three parameters which define this solid line, it was found that the maximum likelihood method did not provide adequate constraints. James has tried a method which minimizes the quadrature sum of the number of standard deviations by which each of three statistics are away from their expectation values. These statistics are $F(\rho) = 1/m\ \Sigma \ln (\Gamma_{fi}/\langle\Gamma_{fi}\rangle)$,[1] a runs test,[29] and the number of points above the median, which for a Porter-Thomas distribution is ∿0.47 of the mean. A better fit in Figure 10 is obtained if two Lorentzian distributions are permitted, one at 550 eV with a width of ∿125 eV and a peak of ∿3.0 meV and the other at 1100 eV with a width of ∿105 eV and a peak of ∿2.1 meV. This preferred fit gives a coupling width of 115 ± 25 eV. In addition to these two structures, there is clear

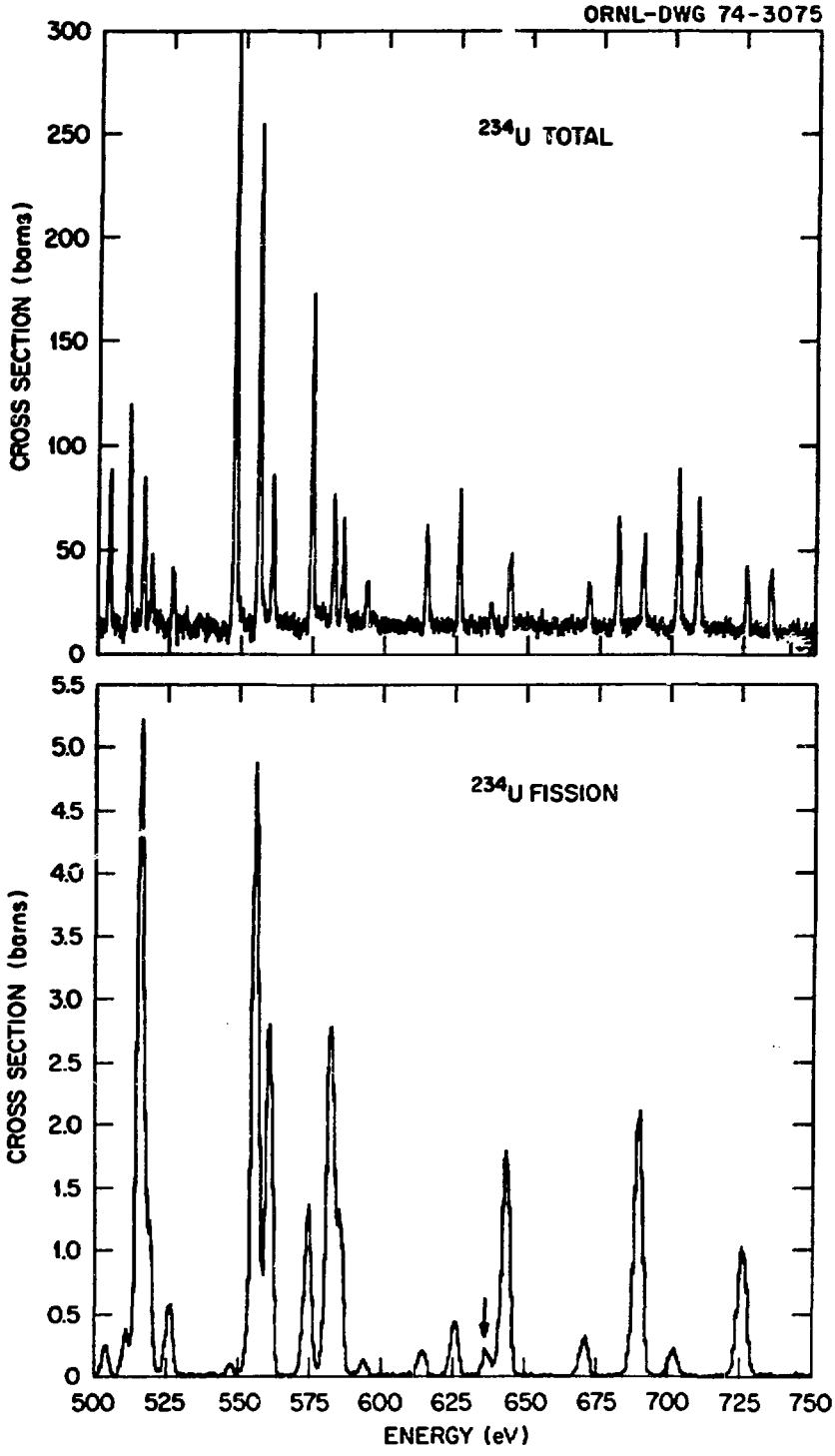

Figure 9. Fission and Total Cross Sections of ^{234}U.

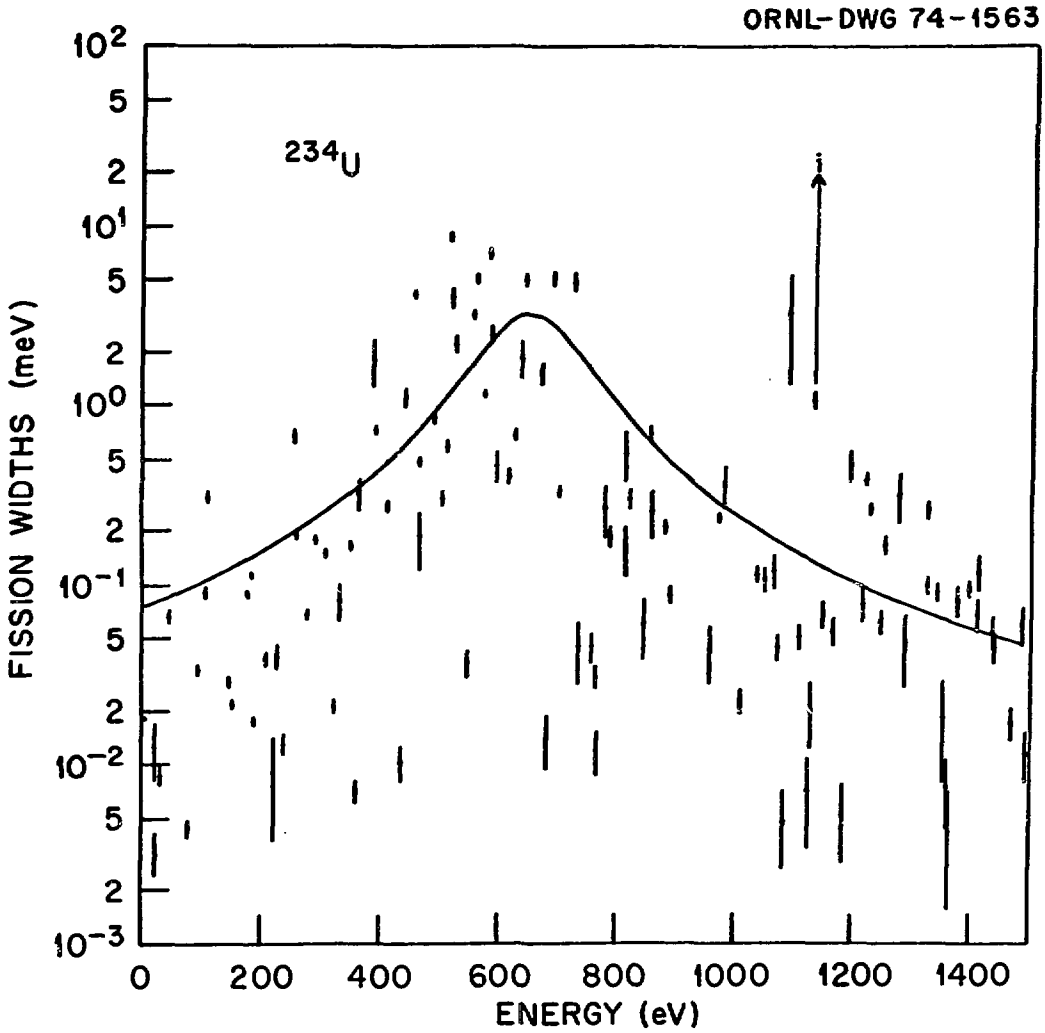

Figure 10. Fission Widths of ^{234}U vs Neutron Energy.

evidence for additional higher energy intermediate structure levels at 3100, 4575, 7845, 11886 and 13072 eV giving a class-II level spacing D_{II} of 2.1 ± 0.4 keV. The fission widths of each of these 5 class-II levels can be obtained from the fission data and an average neutron width. The fission widths of the 7 class-II states are 30, 16, 14, 13, 55, 11 and 24 meV, giving an average value of 23 meV.

Fission cross section measurements were also made up to 0.9 MeV with an energy resolution $\lesssim$ 1%. In addition to the supposed vibrational level at 310 keV similar structure was observed at 550 and 750 keV. It had been suggested by Lynn/35/ that the structure at 310 keV could be due to a vibrational level which gives fission strength to the class-II levels. From the analysis of the data near 310 keV it is deduced that the average class-II fission width at low energy would be only 7.4 meV, a factor of three smaller than the experimental determined value. This result indicates that the low energy levels derive strength from the other vibrational levels at 550 and 750 keV.

This fission measurement on ^{234}U was carried out by G. D. James, J. W. T. Dabbs, and N. W. Hill, and the transmission measurements and their analysis by G. D. James, J. A. Harvey, N. W. Hill, and R. H. Schindler. A complete paper on this work is being prepared for publication by James.

c. Subthreshold Fission in ^{240}Pu and ^{238}U

^{240}Pu was thought to be another nuclide with narrow class-II states and weak coupling to class-I states. Earlier measurements/39/ of the fission cross section of ^{240}Pu resolved fine structure resonances in the first fission cluster at ~800 eV and several resonances in the clusters at 1410, 1900 and 2700 eV. G. F. Auchampaugh (LASL) and L. W. Weston (ORNL) have recently measured ^{240}Pu at ORELA with better resolution and statistics in order to obtain the details of these lower energy fission clusters (to study the coupling between class-II and class-I states) and to search for class-II states in the higher energy clusters. The fission and capture data are measured simultaneously using two liquid

scintillators with pulse shape discrimination. The upper part of Figure 11 shows a small portion of the fission and capture rate data from a 9-gm sample of ^{240}Pu at 20 meters. Two resonances at 1402 and 1409 eV in the second cluster and two at 1918 and 1950 eV in the third cluster show large fission and small to moderate capture (equivalent to neutron width). The small resonance at 1937 eV has a fission width about a factor of 4 smaller than those of its two neighbors. The data on the first 4 fission clusters (and possibly the next two) are expected to give significant information on the coupling between class-I and class-II states. The analysis of the data is in progress.

Subthreshold fission has also been reported[40] in ^{238}U. Two strong fission clusters were observed at 720 and 1210 eV and 6 weaker clusters at higher energies shown at the bottom of Figure 11. The 720-eV and 1210-eV resonances seem to be almost pure class-II levels as they each contain ~70% of the fission of the cluster and have very small neutron widths. These data were taken with an energy resolution of ~1% and, hence, above 2 keV the resolution is not sufficient to see individual fine structure resonances. It would be very interesting to have much higher resolution in order to observe the details of the fission clusters above 2 keV.

V. Polarized-Neutron Polarized-Target Fission of ^{237}Np and ^{235}U and Spin Determinations

The most difficult and complex neutron experiment performed on ORELA is the cooperative experiment between LASL and ORNL using polarized neutrons and polarized targets of ^{237}Np and ^{235}U. The interest in ^{237}Np was to determine the spins of the individual resonances in the lowest subthreshold fission cluster and to determine whether the higher energy fission clusters are each composed of resonances of only one spin state. Since a paper describing the experimental equipment in detail and reporting the ^{237}Np results has been published[41] only a very brief summary will be given here. Some of the details of the experiment are shown in Figure 12.

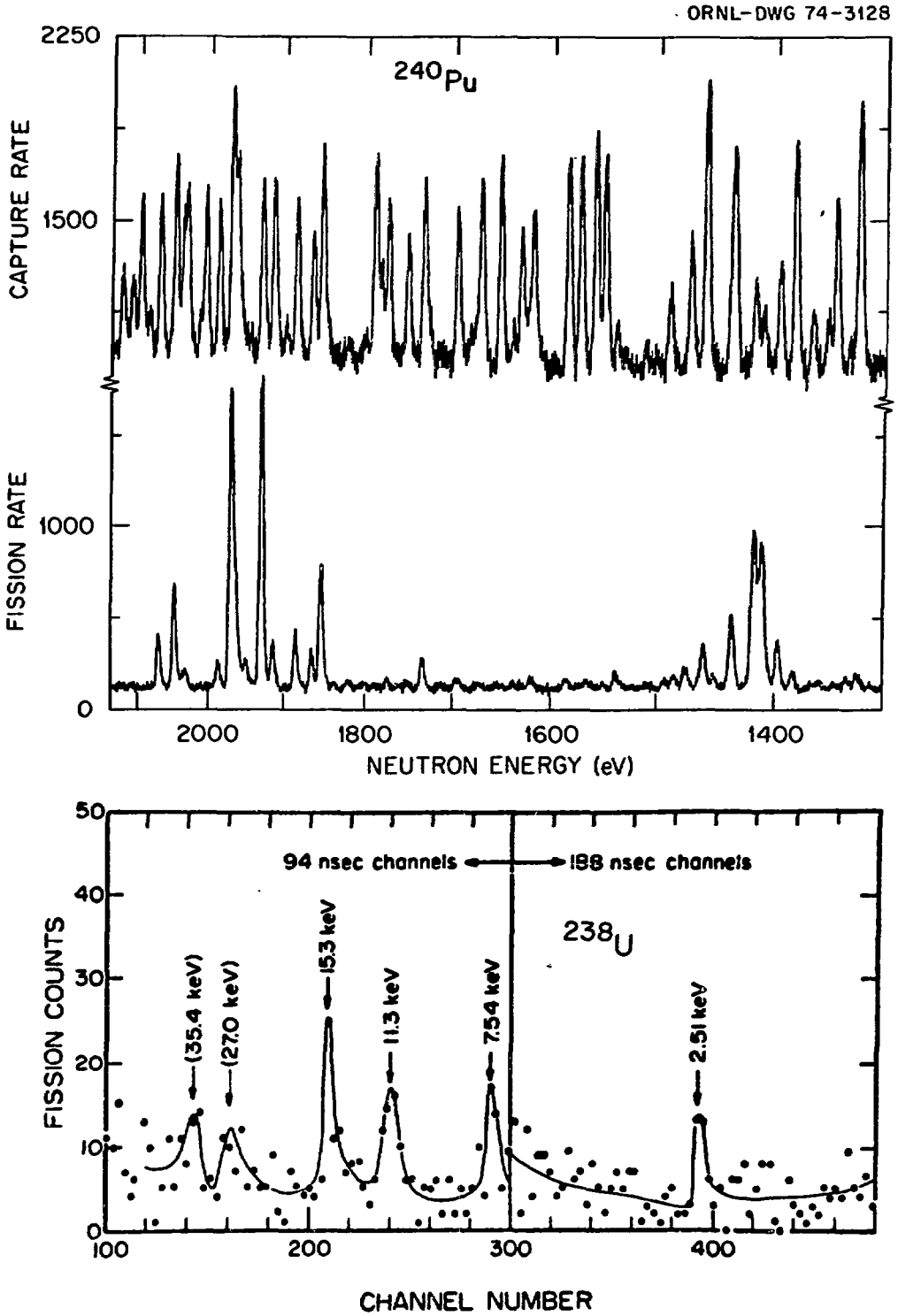

Figure 11.
Upper: Fission and Capture of ^{240}Pu
Lower: Fission of ^{238}U

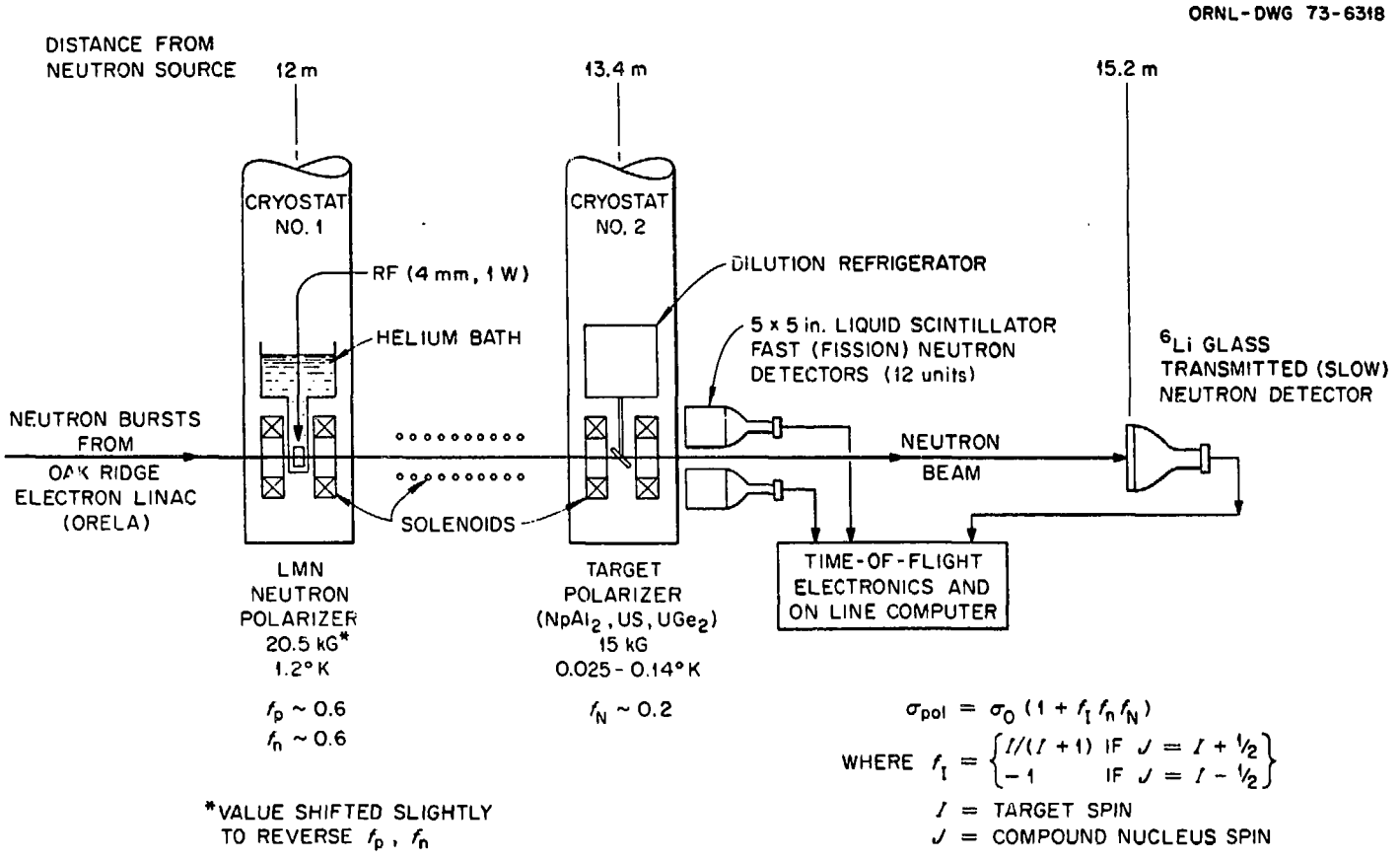

Figure 12. Schematic of LASL-ORNL Polarized Fission Experiments.

A neutron beam with ∿55% polarization was produced using the method proposed by Shapiro[42] by passing a beam of neutrons through a polarized proton target (LMN). The ferromagnetic $NpAl_2$ sample was cooled by a ^3He-^4He dilution refrigerator and with a superconducting magnet a polarization of ∿20% was achieved. Fission neutrons were detected using liquid scintillators with pulse shape discrimination and the transmission detector was a ^6Li glass scintillator. The fission data in the region of the first fission cluster and a sample of the transmission data are shown in Figure 13. From the fission measurement it is obvious that all 9 resonances in this 40-eV fission cluster are spin 3. The spins of 14 other class-II structures below 1 keV were also determined; 9 were J=3. Of these, four had atleast 2 resonances, three apparently contained only a single resonance, and seven above 400 eV probably consisted of unresolved resonances. The transmission data shown in Figure 13 unambiguously permit the spin assignments of all resonances in this energy region. Spin assignments were made to 92 resonances below 102 eV from the transmission measurements but 12 of these are tentative. Confirmation of 8 of the 9 resonances observed in fission between 26.6 and 50.4 eV was obtained in the transmission measurement. A comparison of these polarized neutron results with those of Kuiken et al[43] indicates K=2 is predominant for both J=2 and J=3 resonances with some contribution from J:K=3:3 and J:K=2:1 states.

For the polarized measurements with ^{235}U the compound uranium monosulphide was used. Again fission events were determined by neutron detection. Since the results of this work have also been published[44] recently, only a brief summary will be included here. The spins of 65 resonances up to 60 eV have been assigned; 44 spin 4^- and 21 spin 3^-. Over the last 20 years many attempts have been made to determine the spins of the resonances in ^{235}U by several other techniques such as capture, scattering and mass asymmetry. In general there is poor agreement with the results from these indirect methods. Only one[45] of the four capture

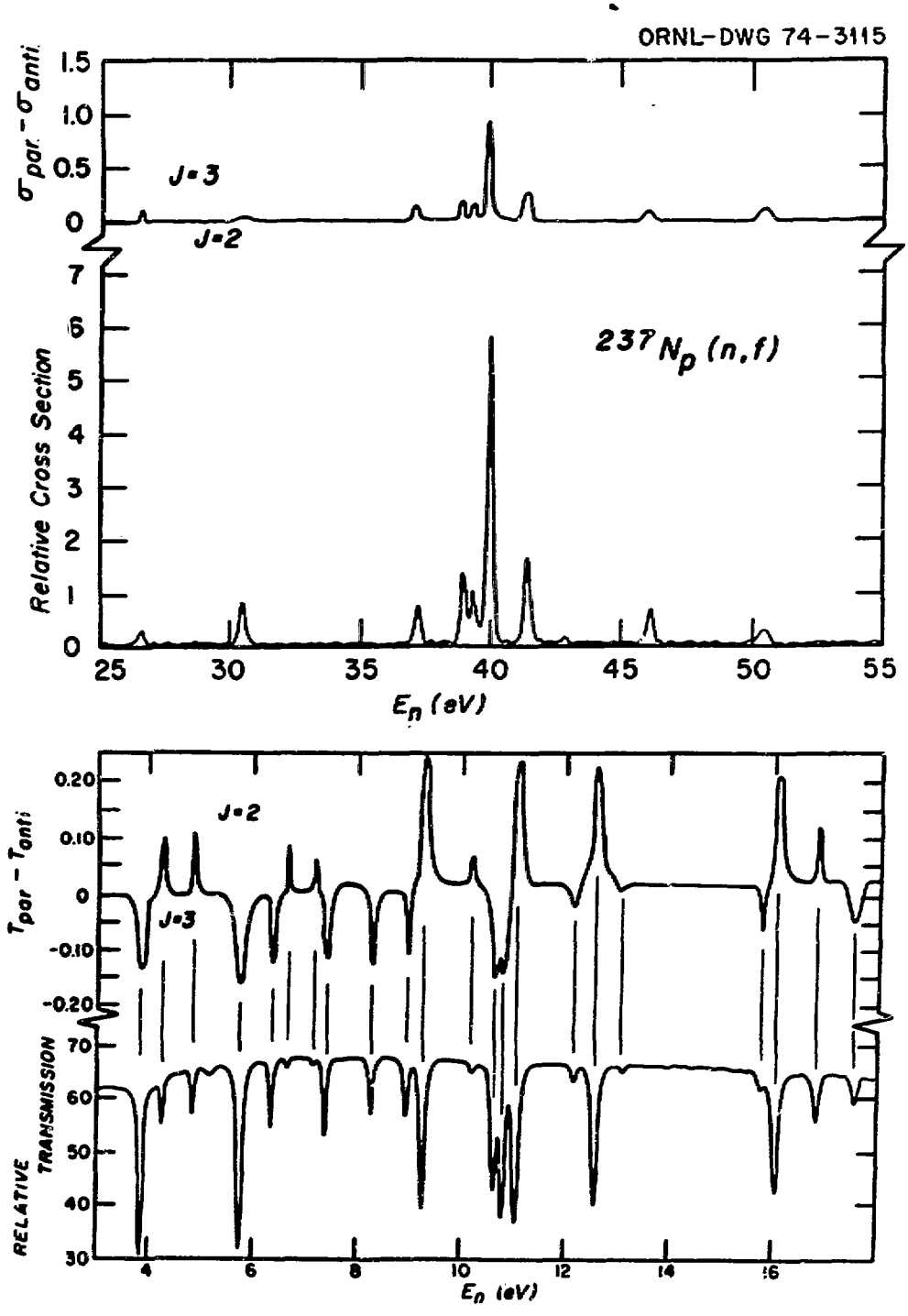

Figure 13. Polarized Fission and Transmission Data for ^{237}Np.

measurements and other polarization measurements give complete agreement with the ORELA measurements. The number of spin assignments from this work is significantly larger than from any of the other methods. A comparison of the spin assignments with recent data[46] on the angular distribution of fission fragments from aligned ^{235}U reveals the absence of the K=0 channel and an apparent admixing of transition states. It has been suggested[46] that the absence of the K=0 channel implies the lack of availability of nearby K=0 class-II states which couple to the class-I states.

VI. Neutron Capture Reactions

Neutron capture measurements in the 3 to 500 keV energy region have been made at ORELA upon a large number of enriched isotopes throughout the periodic table; in particular those nuclides of interest to nucleosynthesis such as the isotopes of Ca. For example, the abundances of ^{40}Ca and ^{42}Ca are accounted for by explosive oxygen burning, but ^{43}Ca is probably formed by slow neutron capture. Unstable ^{41}Ca is of primary importance for the production of $A \gtrsim 43$ and cross sections for this isotope must be estimated from the systematics derived for the other isotopes. From measurements at ORELA, the radiation widths of s-wave resonances are 4 to 7 times greater than those of non s-wave resonances for the even isotopes. However, in this paper only the capture measurements upon ^{28}Si, ^{206}Pb and ^{207}Pb will be discussed briefly, since these data are related to the question of doorway states and non statistical effects.

The high efficiency, good time-resolution, and low neutron sensitivity of the C_6F_6 scintillator detector system make it an attractive alternate to a NaI(Tl) or Ge(Li) detector when the first excited state of the compound nucleus is $\gtrsim$ 1 MeV above the ground state, as in ^{28}Si+n and ^{207}Pb+n. Hence, these high-bias data are essentially the inverse of the $^{29}Si(\gamma,n_0)$ experiment, but the neutron energy resolution is $\sim$4 times better. This improved resolution is important in analyzing the shape of the resonances. For example, the asymmetry claimed for the

761-keV neutron group in the (γ,n) work[47] can be explained by the observation of 2 resonances 20 and 30 keV lower in energy which were found in the (n,γ) work.[48] Hence, the claim[47] of a strong background cross section derived from this observed asymmetry cannot be used as an argument for a doorway state at this energy. The total radiation widths of the resonances vary greatly from 0.4 to 21 eV and are strongly correlated with the neutron widths. This agrees with the strong correlation between the neutron width and the partial gamma width to the ground state.[47]

Similar (n,γ) measurements[49] upon ^{206}Pb have led to the conclusion that the reported $s_{1/2}$ doorway state observed in the neutron channel is not observed in the photon channel in contradiction with earlier (γ,n) results,[34] but in agreement with recent (γ,n) data.[33] Allen and Macklin[50] have also reported (n,γ) measurements upon ^{207}Pb. These data show that earlier (γ,n) data[51] on ^{208}Pb which reported a large asymmetry of the 41-keV resonance were incorrect. Hence, no anomalous processes need to be postulated in order to explain the small slowly varying background cross section. Recent (γ,n) measurements[52] and measurements using 25-keV neutrons[53] are in agreement with the results of Allen and Macklin.

Since several other speakers will report on high-resolution gamma ray spectra data from resonance neutron capture this subject has not been included in this review. However, an example demonstrating the value of resonance-neutron gamma-ray spectroscopy is shown in Figure 14. The left side of Figure 14 shows that the ratios of the intensities of the 897 and 921-keV gamma-rays in the compound nucleus ^{119}Sn were the same in 3 different experiments. However, from resonance capture the ratios, shown on the right of Figure 14, varied from 0.49 to 1.68. This variation in the ratio was conclusive evidence for the existence of a doublet[54] at 920.5 and 921.4 keV in ^{119}Sn. Another obvious example for resonance capture above a few keV is that one can establish primary transitions from their energy shifts as has been done for resonance capture in ^{57}Fe for neutron resonances up to 30 keV.

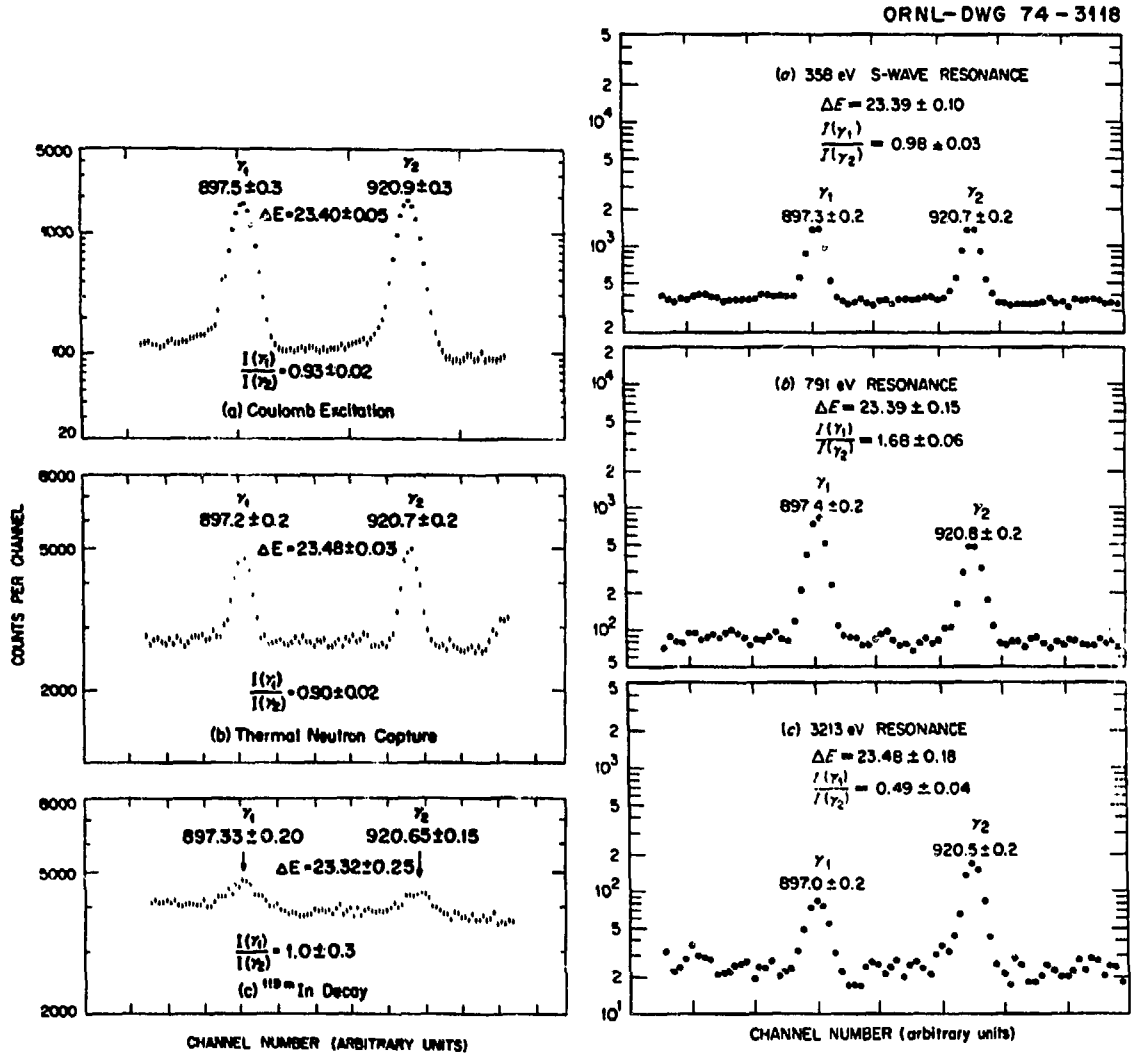

Figure 14. Intensities of 897 and 921-keV Gamma Rays in ^{119}Sn.

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