2 cy

BNL 17023
Conf-720701--5
RECEIVED BY TIC SEP 20 1972

NONSTATISTICAL EFFECTS IN RADIATIVE NEUTRON CAPTURE*

Said F. Mughabghab
Brookhaven National Laboratory, Upton, New York, USA

Nonstatistical aspects of the reaction mechanism of radiative neutron capture in the 3S, 3P, and 4S giant resonances are examined. It is shown that (d,p) and (n,γ) correlations observed in thermal capture in the 3S giant resonance region may be interpreted in terms of valence neutron capture. In the 3P giant resonance, valence neutron capture dominates in nuclei such as ^{95}Mo, ^{96}Zr, ^{108}Pd. The correlations observed in ^{173}Yb(n,γ)^{174}Yb are accounted for in terms of a doorway state. Examples are cited where nonstatistical effects are correlated with a concentration of S- or P-wave neutron strength.

INTRODUCTION AND FORMULATION

In 1934, Fermi and collaborators(1) reported the results of their investigations of neutron interaction with nuclei; two years later N. Bohr(2) enunciated the statistical theory of the compound nucleus according to which the decay mode of the compound state is independent of its method of formation. A significant and important theoretical development in neutron capture in 1959 was the complete mathematical formulation of the theory of channel and direct capture by Lane and Lynn.(3) This theory sparked and stimulated considerable experimental and theoretical effort in the study of simple reaction mechanisms in neutron capture. Some of these simple processes are described in Fig. 1. These are:

1. The direct potential or hard sphere capture in which an incident s-wave neutron is scattered by the boundary of the nuclear surface into a low lying p-state. In the process enhanced electric dipole radiation is emitted. The amplitude of the direct capture component can be experimentally detected through its interference with the amplitude of the compound nucleus component.

2. The channel capture of Lane and Lynn or valence neutron capture of Lynn(4) in which an incident neutron is scattered via a resonance undergoing a transition to a low-lying final single particle state. Specialized to P-wave capture, the important transitions are p → s and p → d. By considering the motion of a neutron in a potential well, Lynn(4) derived simple expressions for electric and magnetic partial radiative widths. Implicit in this derivation is the neglect of core excited states in the radiative process, i.e., the valence neutrons are not coupled to the giant dipole resonance. Recently Lane(5) examined the justification of this assumption and advanced the interpretation that it is due to a compression effect at neutron threshold. This arises because of specific properties of the wave function outside the nuclear surface.

*Work supported by the U.S. Atomic Energy Commission.

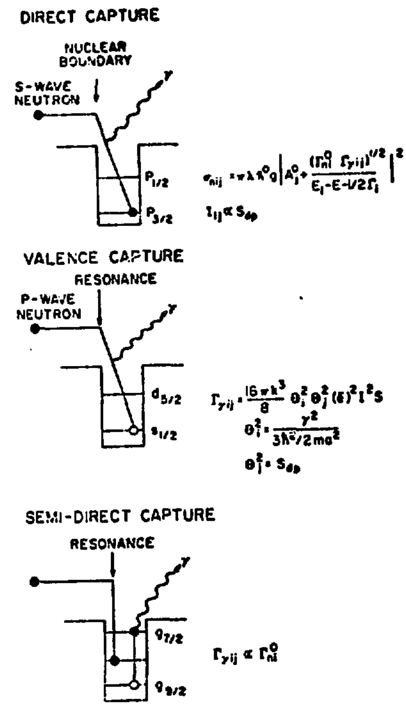


Figure 1

Description of simple reaction mechanisms of neutron radiative capture in terms of direct capture, valence neutron capture, and doorway state formation.

The partial radiative width for electric dipole radiation is represented by the expression

$$\Gamma_{\gamma if} = \frac{16\pi k^3}{9} \Theta_i^2 \; \Theta_f^2 \left| \bar{e} \int_0^\infty dr U_i r U_f \right|^2 \times \frac{\left| j'IJ_i \| Y^{(1)} \| J''IJ_f \right|^2}{2J_i + 1}$$

where k is the photon wave vector, Θ_i^2 and Θ_f^2 are reduced dimentionless widths of the initial and final states respectively and are given by $\Theta_i^2 = \gamma_i^2 | \gamma_{sp}^2$, $\Theta_f^2 = S_{dp}$. The natural effective charge of the neutron is given by

$$\bar{e} = \frac{eZ}{A}.$$

The radial overlap integral is evaluated by Lynn using a Saxon-Woods potential with a spin orbit coupling term. If one uses simple harmonic oscillator wave functions one[8] arrives at values which are $\approx$ 15% of those derived by Lynn. The reduced matrix element for the operator $Y^{(1)}$ can be written as

$$\frac{|\langle J'IJ_i\|Y^{(1)}\|j''IJ_f\rangle|^2}{2J_i+1} = \frac{3}{4\pi}(2J_f+1)(2j'+1)(2j''+1)(2\ell'+1)W^2(j'J_ij''J_f;\,I1)$$

$$\times\, W^2(\ell'j'\ell''j'';\tfrac{1}{2}1)\; C^2_{\ell'1}(\ell''0;00)$$

Attention is drawn to the fact that the single particle reduced width of the initial state is given[7] by

$$\gamma^2_{sp} = \frac{3\hbar^2}{2ma^2}$$

3. The semidirect process[8] or capture through a doorway state.[9] In this reaction mechanism an incident neutron creates an intermediate or doorway state, such as 2p-1h state. Subsequently a particle and hole combine with the formation of enhanced radiation. This concept was invoked by Bartholomew, et al.[10] to interpret the (d,pγ) measurements and by Chrien, et al.[11] to explain the correlations observed in the $^{93}Nb(n,\gamma)^{94}Nb$ reaction.

Because of these considerations, one can thus write down for the radiative decay amplitude

$$\Gamma^{\frac{1}{2}}_{\gamma if} = C_1\,\Gamma^{\frac{1}{2}}_{\gamma if}(sp) + C_2\,\Gamma^{\frac{1}{2}}_{\gamma if}(ds) + C_3\,\Gamma^{\frac{1}{2}}_{\gamma if}(cn)$$

where the successive terms on the right hand side are components due to single particle, doorway state, and compound nucleus formation. Because of the extreme complexity and random character of the initial state,[12,13] $\Gamma^{\frac{1}{2}}_{\gamma if}(cn)$ is normally distributed with zero mean. In most cases as is well born out by experiments[14,15] the last term dominates and as a result the observed distributions and intensity variations of the γ ray spectra conform to a complete statistical discription. The success of the statistical model is reflected for example in its ability to determine spins of capturing states by the cascade γ ray method and to assign spins to final states by Bollinger's average technique.[16] Nonetheless one could investigate nuclei where the contribution of the single particle component is expected to dominate. What one might hope for, as emphasized by Lane and Lynn,[3] is that resonances with large reduced widths and nuclei with low-lying states which are characterized by simple configurations would exhibit nonstatistical properties. It is the aim of this presentation to examine these cases and attempt to understand them in terms of a simple unified reaction mechanism.

METHODS OF STUDYING NONSTATISTICAL EFFECTS

Several methods and techniques have been developed in order to investigate nonstatistical effects in radiative neutron capture. These include:

1. Correlations between thermal γ ray reduced intensities or reduced partial radiative widths with the (d,p) spectrocopic factors. In mass region

A = 50, large and significant correlation coefficients between reduced thermal intensities and spectroscopic factors have been reported for a number of nuclei. In mass region A = 100, important correlations occur in resonance neutron capture in Nb and ^{98}Mo while at higher mass regions correlation coefficients have been reported in thermal capture in the 82 neutrons closed shell nuclei(17) ^{138}Ba, ^{140}Ce, and ^{142}Nd.

2. Study of direct or hard sphere capture by interference analysis between the direct and compound nucleus amplitudes as shown in Figure 1. The best reported examples(18,19) are ^{59}Co and ^{238}U.

3. Correlation analysis between the radiation decay width $\Gamma_{\gamma if}$ and the reduced scattering width, Γ^{o}_{ni} in resonance neutron capture. The reported cases will be examined in detail later on.

4. Study of the statistics of partial radiative widths and particularly departures from χ^2 distribution with one degree of freedom. Many nuclei had been examined for possible departures from a Porter-Thomas distribution. However, the majority of the cases are found to obey such a distirubution. Recently, Becvar(20) investigated the distribution of partial radiative widths of the reaction ^{149}Sm(n,γ)^{150}Sm and concluded that there is a certain probability of a departure from a Porter-Thomas distribution. Specifically, he found that for resonances of the $J^{\pi} = 3^-$ and 4^- and 13 final states with $J^{\pi} = 3^+$ and 4^+ $\nu = 1.64^{+0.22}_{-0.18}$ with a probability that $\nu = 1$ being only 0.05%.

According to channel or valence neutron capture, the partial radiative widths are correlated with the reduced neutron widths and as a result the distribution of partial radiative widths must obey a Porter-Thomas distribution.

5. Study of anamolous bump in different reactions such as (n,γ), (d,pγ), (γ,γ').(10,21)

Now let us focus our attention on the available data in order to locate the regions of nonstatistical effects. An inspection of Figure 2 reveals that there are three regions where pronounced departures from the extreme statistical model have been observed. These are:

(1) $40 \leq A \leq 70$

(2) $A \approx 100$

(3) $A \approx 160$.

When one compares these regions of nonstatistical effects with variations of the s and p-wave neutron strength functions, one immediately recognizes the fact that these are associated with the maxima of the 3s, 3p, and 4s giant resonances. Because of this circumstance, the view that these nonstatistical effects are associated with a concentration of s or p-wave neutron strength is advanced. Each region of nonstatistical effects will separately be discussed in detail.

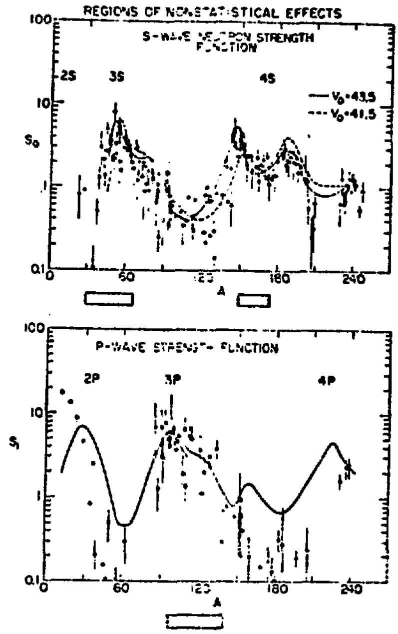


Figure 2

Nonstatistical effects seem to be present in mass regions where the s- or p-wave neutron strength functions peak, i.e., where the single particle states are located at zero neutron energy.

CORRELATION IN THE 3S GIANT RESONANCE

A large body of thermal capture data is now available which indicate that in mass region[22-25] from ^{40}Ca to ^{64}Ni large and significant correlation coefficients between reduced intensities and (d,p) spectroscopic factors occur. This characteristic feature had been presented as a piece of evidence for direct or hard sphere capture. In this presentation we shall show that this point of view is not necessarily valid and shall demonstrate that it is a resonance phenomenom because of the proximity of either positive or negative energy resonances to the thermal region as pointed out by Lane.[5] Because of this circumstance, then the observed correlations can be explained in terms of the valence neutron model. The best clear cut illustration [26] of this situation can be found in the $^{58}Ni(n,\gamma)^{59}Ni$ reaction. The thermal cross section of ^{58}Ni is known to be dominated by an extraordinarily strong bound level whose parameters are determined with sufficient reliability[27,28] to allow calculations in the framework of the valence neutron model. Detailed shape analysis of the total cross section by Garg, et al. show that the parameters of the level are E_0 = -28.5 keV, Γ_n^0 = 98.5±5.4 eV and Γ_γ = 9.0 eV. The important valence neutron transitions in this mass region are $s_{\frac{1}{2}} \rightarrow p_{\frac{1}{2}}, p_{\frac{3}{2}}$. Calculations of partial radiative widths in the frame work of the valence neutron model yields:

$$\sum_{sp} \Gamma_{\gamma if} = 7.5 \text{ eV}$$

The summation is carried out over $p_{\frac{1}{2}}$ and $p_{\frac{3}{2}}$ low lying states with large spectroscopic factors.

If one assumes that doorway state contribution is negligible and that interference terms average out, one can write down:

$$\Gamma_\gamma = \Gamma_\gamma(sp) + \Gamma_\gamma(cn)$$

with the aid of $\Gamma_\gamma(cn) = 500$ mV as obtained from a study of the systematics[29] of total radiative widths, one obtains $\Gamma_\gamma = 8.0$ eV which is in good agreement with the value $\Gamma_\gamma = 9.0$ eV derived by Garg, et al. One can then calculate the γ ray thermal intensities on the basis that they are due totally to the tail of the bound level. The results are shown in Figure 3 and again one notes the good agreement between measured[30] and calculated intensities. Similar results for $^{50}Cr(n,\gamma)^{51}Cr$ are shown.

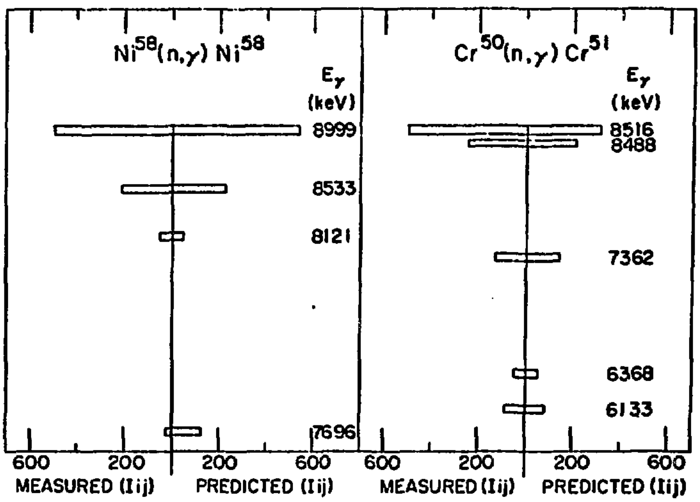


Figure 3

Comparison of measured and predicted thermal γ ray intensities.

At this point it must be noted that γ ray spectra due to keV capture[31,32] in ^{54}Fe and ^{48}Ti are at present available. These measurements indicate that keV neutron capture is very similar to thermal capture, which suggests that thermal capture in ^{48}Ti and ^{54}Fe is dominated by the effect of the positive energy resonances at 17.6 and 7.8 keV respectively. Analysis of the total cross section of Ti by Garg, et al.[28] show the requirement that $\Gamma_\gamma = 8.1$ eV for the 17.6 eV resonance of ^{48}Ti. An independent support for this large value of the total radiative width of ^{48}Ti comes from measurement of the absorption resonance integral. On the basis of these results one could obtain an idea of the partial radiative widths of the17.6 keV resonance of ^{48}Ti. The valence neutron model predictions show that the calculated values falls short of the experimental values by about a factor of four. It is interesting to point out that similar conclusions are reached for ^{54}Fe and ^{64}Ni. This can be interpreted as an enhancement in the radiative process; such an enhancement can be achieved by considering, for example, an effective charge e for the neutron instead of the usual $\bar{e} = eZ/_A$. This then would represent a departure from the valence neutron model. One can then possibly describe the results in terms of capture through a doorway state.

Additional light on the reaction mechanism of radiative neutron capture in the 3s giant resonance is provided by the measurements of the ground state radiative widths by Jackson and Strait[33] who utilized the (γ,n) reaction. Calculations by Bhat, et al.[34] revealed that for the resonances at 50.2, 12.5, and 27.9 keV in ^{52}Cr, ^{60}Ni, ^{56}Fe, respectively the agreement between the predictions of the valence neutron model and the experimental values is remarkably good. It is particularly interesting to note that, at higher neutron energies, the experimental values, when averaged over resonances, are again greater that the valence neutron model predictions by about a factor of four. This can be interpreted as an enhancement in the E1 radiation and, as pointed out previously, could be effected through a 2p-1h excitation. Similar enhanced transitions have been observed by Jackson and Strait[35] in M1 radiative excitation of p-wave resonances in ^{56}Fe+n. This was described in terms of a doorway state. Furthermore, Block, et al.[36] reported that the total radiative widths are correlated with the reduced neutron widths of $^{50,52,53,54}Cr$, ^{60}Ni, and ^{51}V resonances. A doorway state interpretation was advanced by these authors.*

THE VALENCE NEUTRON MODEL IN THE 3P GIANT RESONANCE

Experimental evidence which is accumulating indicates that nonstatistical effects due to valence neutron or doorway state capture are associated with a concentration of s- or p-wave neutron strength in a limited neutron energy interval. Around the mass region A = 100, ^{98}Mo and ^{96}Zr present us with the best illustrations of this phenomenon. Examples pertaining to the 4s giant resonance will be cited in the next section. At first, let us turn our attention to ^{98}Mo. The resonances at 429, 612, 818 eV are characterized by p-wave reduced neutron widths which are about a factor of five larger than the average value. The measurement of γ ray spectra from individual resonances in ^{98}Mo were initially carried out at the Brookhaven National Laboratory fast chopper facility of the High Flux Beam Reactor. In order to extend the neutron energy region, the measurements were repeated at the Oak Ridge Linear Accelerator, in collaboration with G. G. Slaughter, with better neutron energy resolutions. Figure 4 illustrates the importance of valence neutron transitions in the spectra of the 429, 812, and 818 eV resonances. One immediately recognizes certain regularities in the spectra of these strong p-wave resonances.

---

*See also Reference 36a.

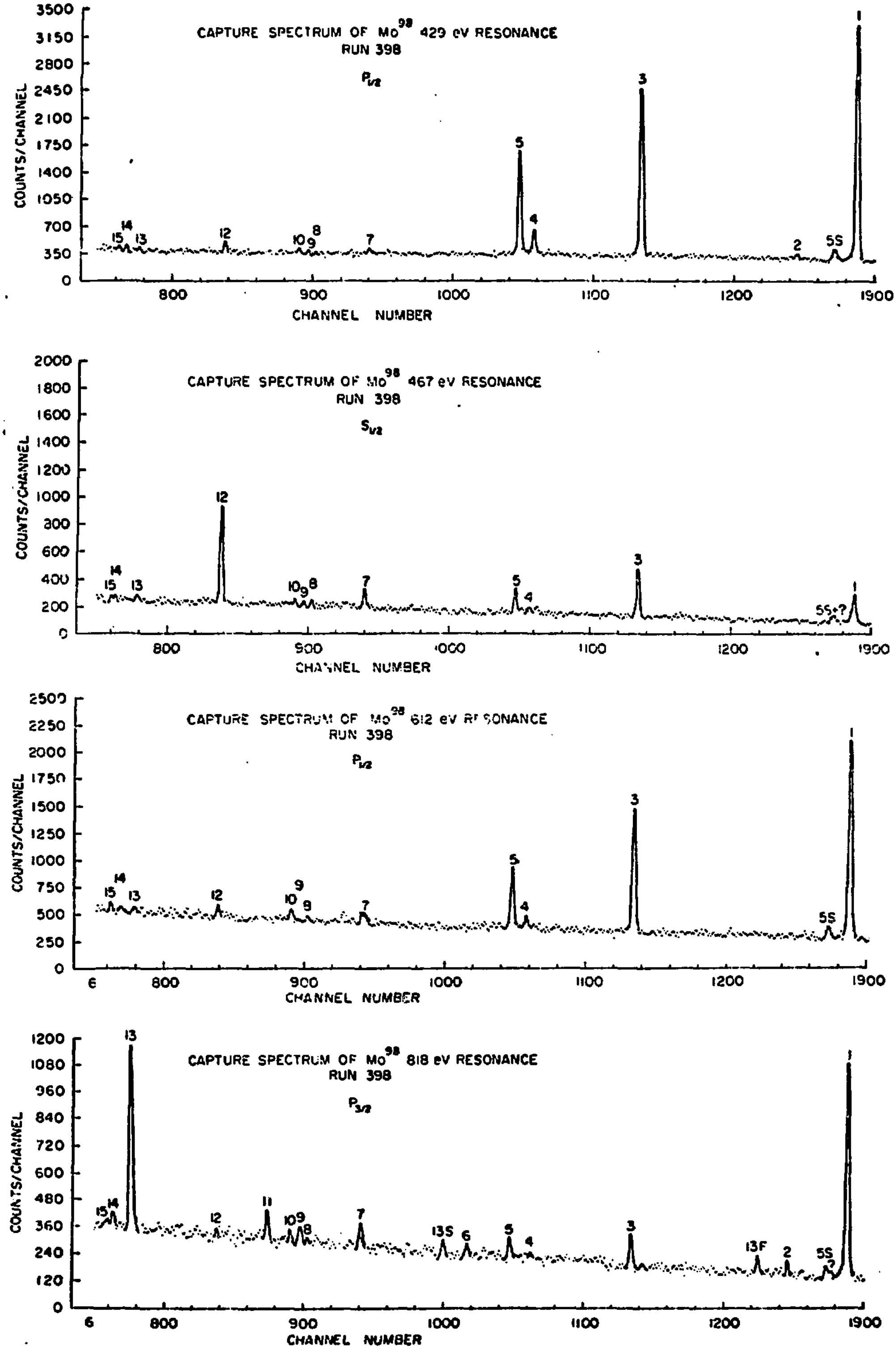
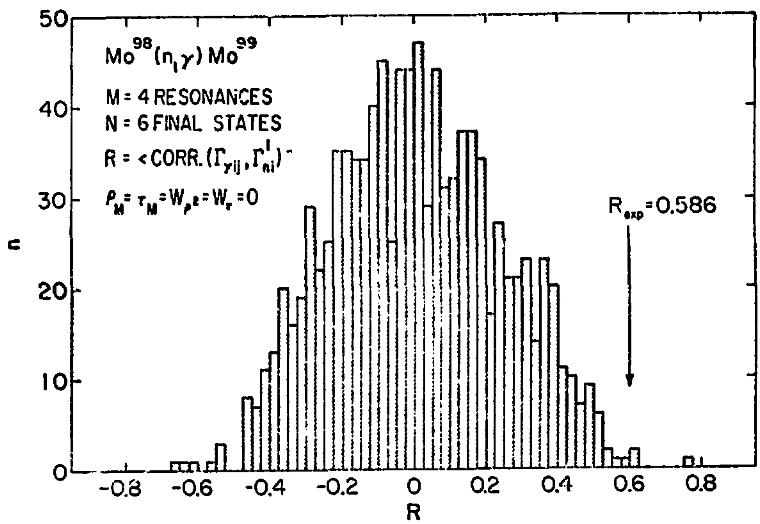


Figure 4: Neutron capture in ^{98}Mo p-wave resonances at 429, 612, and 818 eV and in the s-wave resonance at 467 eV. Note that peak 12 corresponds to an E1 transition to an E_x = 1033 keV with ℓ = 1.[37]

Figure 5

Study of the correlation coefficients between partial radiative widths and reduced neutron widths of ^{98}Mo in terms of a Monte Carlo calculation.



1. γ rays from these resonances are strongly feeding the ground state of ^{99}Mo.

2. What is more striking is the fact that the γ ray spectra of the 429 and 612 eV resonances are almost identical.

Clearly, these features are not in accord with the statistical model. A correlation analysis between partial radiative widths and p-wave reduced neutron widths in terms of a ~~Monte Carlo~~ analysis exhibited a significant correlation coefficient as shown in Figure 5.

In addition the γ rays from these resonances populate strongly low lying states with large single particle components as indicated by the (d,p) spectroscopic factors. A correlation analysis between reduced γ ray strengths and (d,p) spectroscopic factors[37] revealed significant correlation coefficients. These observations had already been made by our own group[38] and those at Geel.[39] What was intriguing in the results was the weak presence of the γ lines labelled by 3 and 5 in the 818 eV resonance. When one recognizes the $p_{3/2}$ spin assignment of the 818 eV resonance[40] and the $d_{3/2}$ character of the final states corresponding to lines 3 and 5, it immediately becomes clear that these are transitions of the type $p_{3/2} \rightarrow d_{3/2}$. Such transitions are inhibited in the single particle model because of the angular momentum coupling coefficients. This observation strengthened by the existence of both type of correlations $\rho(\Gamma_{\gamma if}, \Gamma^{o}_{ni})$ and

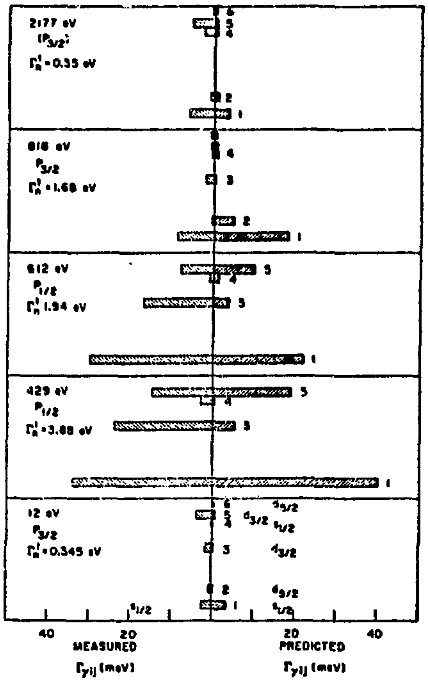


Figure 6

Comparison of measured and predicted partial radiative widths of ^{98}Mo for low lying states with significant spectroscopic factors.

$\rho(\Gamma_{\gamma if}/E_\gamma^3, S_{dp})$ motivated us to evaluate the magnitude of the ^{92,93}Mo partial radiative widths[41,43] in the frame work of the valence neutron model.[4] The results for ^{98}Mo are summarized in Figure 6. As indicated, not only the variations of the various $\Gamma_{\gamma if}$'s are well described for the resonances at 12, 429, 612, 818, and 2177 eV but also the absolute magnitude is in remarkable agreement with the model predictions. At this point I would like to emphasize that the absolute intensities of the present results are normalized to W. Kane's[43] ^{197}Au measurements and that the calculated values are based on the more recent resonance parameters of Weigmann, et al.[44] and Harvey, et al.[45]

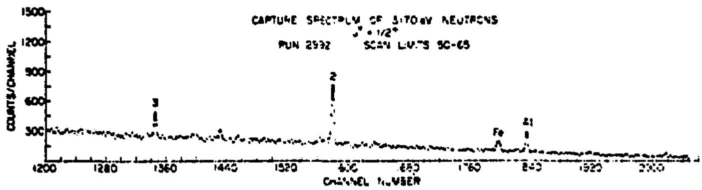


Figure 7

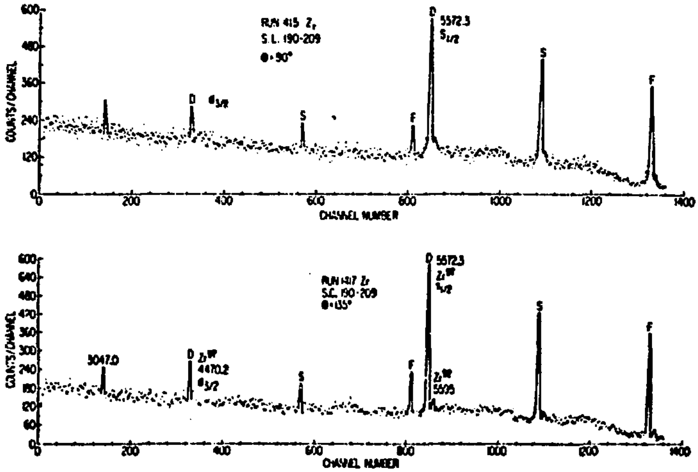
Neutron capture in the 3.7 keV s-wave resonance of ^{92}Mo. Transition No. 2 is feeding the first excited state of ^{93}Mo at 942 keV ($s_{1/2}$).

The ^{92}Mo measurements previously carried out at Brookhaven National Laboratory are extended to higher neutron energies by Wasson and Slaughter at ORELA. These investigations[46,47] reveal enhanced M1 radiative strength comparable to the E1 strength in capture in the 3.7 keV s-wave resonance. In addition, one interesting result of the ORELA preliminary data is that some transitions in s-wave neutron capture may be identified as E2 in character, and as such are exceptionally enhanced. Below 20 keV, the dominance of the transition (E_γ = 7124 keV) populating the first excited state at E_x = 942 keV is a violation of the extreme statistical model.

The success of the valence neutron model in the 3p giant resonance motivated us to study other nuclei in the mass region A = 100. A crucial test of the valence neutron model was provided by neutron capture in ^{96}Zr. This nucleus has similar neutron structure as ^{98}Mo, i.e., 50 neutrons forming a closed major shell plus six others in a filled $d_{5/2}$ orbit. On the basis of the (d,p) data, the ground state of ^{97}Zr had been assigned as a pure $s_{1/2}$ single particle state. The neutron resonance at 302 eV of ^{96}Zr had been identified by Rimawi(48) as a p-wave resonance on the grounds of observation of a strong γ ray (5177 keV) feeding the ground state of ^{97}Zr. An independent support for the p-wave interpretation of this resonance comes from the measured thermal cross section ($\sigma_{n\gamma}$= 23±5mb) when compared with a calculated value of 123 mb on the grounds that the resonance is s-wave in character. It must be emphasized that this resonance has a p-wave reduced width which is three times larger than the strongest resonance in ^{98}Mo. In order to compare with the predictions of the valence neutron model, a knowledge of the spin of the resonance is necessary. As a result, angular correlation measurements were carried out(49) at BNL with a 50 cc Ge Li detector at angles of 90° and 135° with the neutron beam direction. When suitably normalized, the symmetry in the angular distribution (Figure 8) establishes the spin of this resonance as J = 1/2. The absolute intensities were determined at ORELA by Wasson and Slaughter by an intercomparison of the ^{97}Zr spectrum with that of 11.8 eV ^{195}Pt spectrum. The absolute intensity of the 7920 keV γ ray is taken as I_γ = 75±5 photons per 10^3 capture. These measurements showed that the intensity of the γ ray populating the ground state of ^{97}Zr (E_γ = 5571 keV) is 860 photons per 10^3 capture ($\Gamma_{\gamma ij}$ = 219 mV) while that feeding the first excited state is 140 photons per 10^3 capture (65 mV). The valence neutron model predicts values of 211 and 65 mV for the transitions to the ground state, $p_{1/2} \rightarrow s_{1/2}$, and the first excited state, $p_{1/2} \rightarrow d_{3/2}$, respectively.

Figure 8

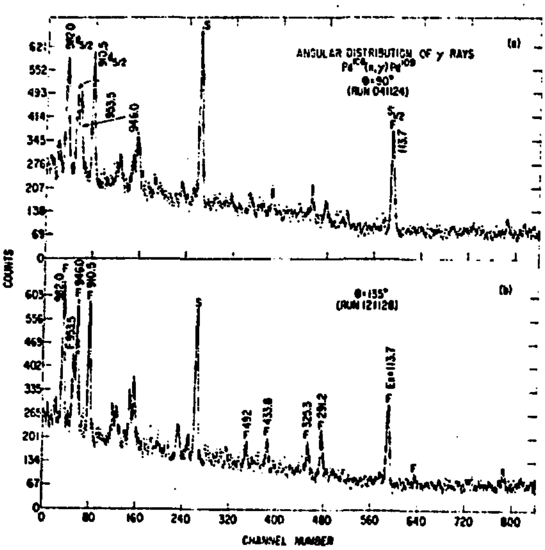
Angular correlation measurements of γ rays due to neutron capture in the 302 eV resonance of ^{96}Zr. The measurements were carried out at the BNL fast chopper facility.



In a continuing effort to study the systematic behavior of valence neutron capture in the 3p giant resonance, the present speaker studied neutron capture in ^{108}Pd in collaboration with Kane and Casten at the BNL monochromator facility of the High Flux Beam Reactor.[50] Measurements of intensities of γ rays from radiative neutron capture in ^{108}Pd were carried out at three energies, the 2.96 eV resonance, off resonance at 2.0 eV, and thermal. The absolute γ ray intensities were determined with respect to the ^{109}Pd decay γ rays which are known with reliable accuracy. Observation of strong transitions to final states with spin and parity $J^{\pi} = 5/2^{+}$ indicated that the spin and parity are $3/2^{+}$. This assignment makes the resonance at 2.96 eV the lowest lying p-wave resonance in this mass region. In order to confirm the spin assignment of this resonance and to establish the spins of the final states, angular correlation measurements were carried out at 90° and 135° as shown in Figure 9. A comparison of the two spectra collected at 90° and 135° exhibits obvious differences in the relative intensities of the γ rays populating the excited states at 113.7,

Figure 9

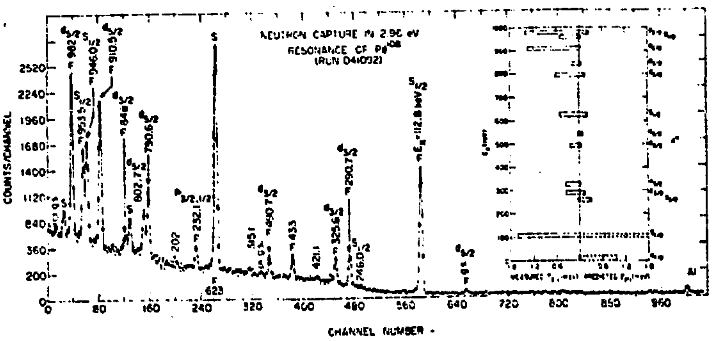
Determination of the spin of the 2.96 eV resonance of ^{108}Pd by observing an asymmetry in the γ ray angular distribution. These measurements, carried out at the BNL monochromator facility, establish the $p_{3/2}$ assignment of this resonance. This gives it the distinction of being the lowest-lying p-wave resonance in this mass region.



946, and 953 keV. These results give further support for the $p_{3/2}$ interpretation of the 2.96 eV resonance. A data run with better statistics is presented in Figure 10. The excitation energy and shell model configuration of the final states (determined by the (d,p) results) populated in the (n,γ) reaction is shown above the full energy peak. Several striking features are indicated in Figure 9:

Figure 10

Portion of the γ ray spectrum due to neutron capture of the 2.96 eV resonance of ^{108}Pd. The excitation energy and shell model configuration of the final state (from (d,p) data) is indicated above each full energy peak. In the insert, a comparison between measured and predicted partial radiative widths is made.



(1) Strong population of the first excited state at 113.7 keV ($s_{1/2}$).

(2) Weak population of all low lying $d_{3/2}$ states at E_x = 291, 326, 433, 491, and 848.

(3) A transition to a low lying state at E_x = 433 keV both in the thermal and resonance spectra, thus indicating that the spin of this state is 1/2 or 3/2.

Previously a level at about this energy (426 keV) had been assigned as a $g_{7/2}$ state in the (d,p) results.[51] An examination of the low energy γ rays shows the presence of two γ rays at energies of 426.3 and 433.7 keV thus indicating the possibility of a doublet in ^{109}Pd at energies of 426.3 and 433.7 keV with spins of 7/2 and 3/2 respectively.

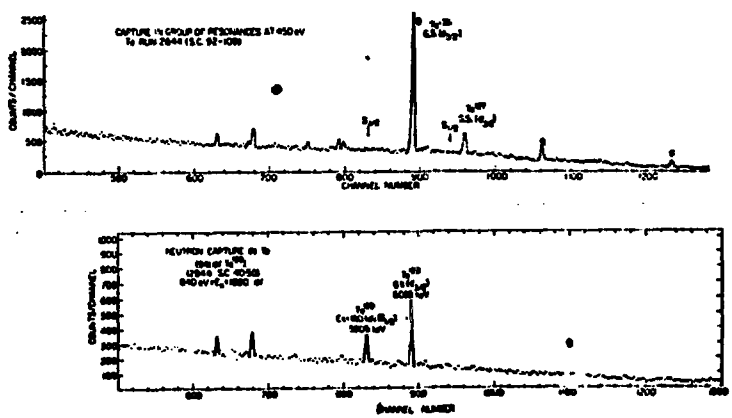
Observations (1) and (2) give signitures of valence neutron transitions. To test this conclusion, calculations of partial radiative widths are made in the frame work of the valence neutron model. Measured and predicted values are presented in the insert to Figure 10. With the exception of the ground state transition ($p3/2 \rightarrow d5/2$) the agreement is remarkably good for low lying states with large spectroscopic factors. This is consistent with observations of Lane that transitions of the type p → s are more single particle than p → d; the latter transitions may lose their strength to the giant dipole resonance.

As one proceeds to larger mass numbers, one finds that some support of the importance of valence neutron transitions is provided by the investigations of Bhat, et al.[53] in the Sn region. The results of these studies show that the γ ray intensities due to neutron capture in the ^{115}Sn 147.9 eV resonance quantitatively obey the model. Specifically, one finds that transition $p_{3/2} \rightarrow s_{1/2}$ (E_γ = 6944 keV) is in very good agreement with the model. In contrast, this transition is notably absent in the spectrum of the 632 eV resonance, although its p-wave reduced neutron width is the same as that of the 147.9 eV resonance. The strongest transition in the spectrum of the 632 eV resonance is $p_{3/2} \rightarrow d_{3/2}$ (E_γ = 6784 keV), which is in violation with the model.

Because of the important role played by strong p-wave resonances in the valence neutron model, an attempt was made to identify such type of resonances in Te.[54] Figure 11 illustrates the γ ray spectra due to neutron capture in energy intervals indicated in the figure. In capture at neutron energies of about 450 eV one is immediately struck by the intense transition (E_γ = 6085 keV) populating the ground state of ^{129}Te, which is a $d_{3/2}$ state. The high resolution transmission data of Tellier, Alix, and Dabbs[55] provide us with the information that ^{128}Te has two resonances at 424 and 435 eV. If these resonances are s-wave in nature, then this transition would be M1 in character and hence would be exceptionally enhanced. Since s-wave capture in the ^{123,125}Te isotopes do not exhibit any enhanced M1 radiation, such a possibility is unlikely although it cannot be excluded. As a result one reaches the conclusion that at least one of the resonances at 424 and 435 eV is a p-wave resonance. There is some evidence for this conclusion from unpublished transmission measurements carried

Figure 11

Capture γ ray spectra of ^{129}Te



out at Argonne National Laboratory by Coté.[56] It is of particular interest to note that the transition to the $s_{1/2}$ first excited state of ^{129}Te is absent. According to the valence neutron model this transition should be about 1.6 times less intense that the ground state transition. In addition, I would like to point out that the same pattern of behavior seems to apply to ^{126}Te in this energy interval: (a) the strongest transition is that populating the $d_{3/2}$ ground state and (b) the transition to the $s_{1/2}$ state at 60 keV is again absent as in ^{128}Te. On the other hand neutron capture in the 941 eV resonance show transitions to both the ground state and first excited state. Transitions to excited p states at higher energies are totally absent. This suggests again, that the resonance at 941 eV is p-wave. The ratio of the calculated intensities for the transitions feeding the ground state and first excited state are in very good agreement with the model on the basis that this resonance is $p_{1/2}$. The pattern of γ ray transitions described for the Sn and Te isotopes here presents some interesting problems in this mass region. Why do some resonances obey the valence neutron model while others do not? Is this related to some specific nuclear structure properties of the neutron resonances? Further experimental and theoretical investigations may shed light on this problem.

CORRELATIONS WITH REDUCED NEUTRON WIDTHS IN THE 4S GAINT RESONANCE

In the 4s giant resonance the problems associated with the study of nonstatistical effects in radiative neutron capture are rendered difficult. Some of these problems are:

(1) Lack of sufficient neutron and/or γ ray energy resolution.
(2) Lack of knowledge of the spin and parity of the final states.
(3) Incorrect spin assignments of neutron resonances.
(4) Small statistical sample.

There are additional inherent difficulties in this mass region. As has been demonstrated in investigations, which were carried out in the 3p giant resonance, nonstatistical effects, such as valence neutron transitions, are most pronounced generally in nuclei where both the neutron reduced widths of the initial and final states are large. This condition is well satisfied for nuclei near magic shells and subshells around mass region A = 100. In contrast, at the 4s giant resonance the fragmentation of single particle strength at the initial and final states curtails the observation of single particle effects. The large deformations of these nuclei accentuates the influence of the giant dipole resonance. Axel[57] investigated the effect of the giant dipole resonance on the γ ray spectra by extrapolating its tail to low energies. By assuming a Lorentzian shape to the dipole giant resonance, he derives an E_γ^5 dependence for the ground state γ ray widths. Bollinger[16] extensively studied with his average method, the variation of the γ ray intensities in the deformed mass region and found that the results are consistent with such an energy dependence.

The BNL fast chopper group initially devoted considerable effort to the study of nonstatistical effects in the 4s giant resonance. Many nuclei were examined with the aim of searching for a correlation between $\Gamma_{\gamma if}$ and Γ^o_{ni}. The experimental problems associated with ^{169}Tm have been discussed by

Chrien[42] and Thomas.[58] Results of experiments carried out at BNL on the reaction $^{163}Dy(n,\gamma)^{164}Dy$ have been reported.[59] More recently the ^{163}Dy case is being reexamined with better neutron resolution at ORELA in collaboration with G. G. Slaughter.[60] The results of these studies is the determination of spins of additional resonances and the discovery that the previously known peak at 105 eV is actually a doublet with energies at 105.9 and 106.7 eV. The spins of neutron resonances at 16.2, 19.6, 50.0, 55.7, 66.0, 72.3, 85.9, 93.9, 105.9, 120, 128, 136, 164, 178, 186, 207, 215, 235, 253, 263, 270, 283 are J = 3, while those at 35.7, 58.8, 71.3, 75.2, 78.7, 106.7, 143, 146, 148, 156, 189, 204, 225, 277, 291, and 299 are J = 2. A detailed correlation analysis has to await the completion of analysis of the scattering widths of the ^{163}Dy data. Recently Danelyan, et al.[61] studied the $^{163}Dy(n,\gamma)^{164}Dy$ reaction with a Ge-Li detector. Unfortunately, their data suffer from the same problems as the old BNL data, i.e., doublet at 105 eV was not resolved.

Additional investigations of nonstatistical effects in the Dy region were carried out by Cole, et al.[62] at the BNL fast chopper facility. In these studies a search for a direct amplitude in the reaction mechanism is made. Lane[63] has shown that the existence of correlations implies the existence of a direct capture amplitude. ^{162}Dy was chosen as a possible candidate because of previous observations[64] which indicated a large total radiative widths for the two resonances at 5.4 and 70.7 eV. In addition the position of the 4s single particle states above the neutron separation energy is located in this mass region. The γ ray spectra due to capture in thermal energy and at 5.4, 70.7, and 267 eV showed features which are characteristic of direct capture. In particular the intensity variation of the γ line E_γ = 5519 keV seems to be correlated with the reduced neutron widths of the resonances. This γ ray populates a state at 351.1 keV which is assigned as a "p"-neutron state with the configuration [521↓] on the basis of the (d,p) data.[65] Analysis of the data in terms of a direct reaction amplitude is still underway.

However, the most vivid illustration of nonstatistical effects in this mass region is illustrated in the reaction $^{173}Yb(n,\gamma)^{174}Yb$. Preliminary results obtained at the 22 m station of the BNL fast chopper facility were reported previously.[66] Since that time, additional data with better neutron resolution was collected at the 48 m station in collaboration with Bartholomew. Because of the availability of high resolution neutron data,[67] the ^{173}Yb example does not have the same problems as ^{163}Dy. In view of this I would like to discuss it in detail. An examination of the resonance parameters of ^{173}Yb shows that there is a clustering of neutron strength in the energy interval 0 - 105 eV. The resonances at 17.7, 31.5, 35.8, 45.3, 76.1, and 105 ev have s-wave reduced widths which are 2 to 5 times larger than the average value.[67,68] This situation is very similar to ^{98}Mo where a clustering of p-wave neutron strength is present in the energy interval 0 - 818 eV. Another important feature of ^{174}Yb is the nuclear structure properties of its final states. Theoretical studies by Bès, et al.[69] showed that the γ vibrational band is characterized by a large component of the two neutron-quasiparticle state $5/2^-[512] - 1/2^-[510]$. This conclusion was supported by the (d,p) data of Burke, et al.[70] Because of these considerations, ^{173}Yb was selected as a possible condidate for observation of nonstatistical effects. Accordingly we measured γ ray spectra from individual resonances of ^{173}Yb at the BNL fast chopper facility using a 4cc and 14cc Ge-Li detectors. At first, it was essential to determine the spins of these resonances. This was achieved by examination of the low energy and high energy primary γ rays. Because the spin and parity of the target nucleus are $5/2^+$, the interaction of s-wave neutrons with ^{173}Yb would excite 2^+ and 3^+ states. Observation of strong transitions to either 4^+ or 1^+ low lying final states would indicate that the spin of a resonance is either 3^+ or 2^+ respectively. In addition two pairs of low energy γ rays, (76.5, 176.6 keV) and (272.9, 287.9 keV) were selected for spin determinations. When both these techniques are combined, one contains definite, unambigous spin assignments. The results of the analysis establish that the resonances at 17.7, 31.5, 45.3, 76.1 (unresolved from 74.5), and 105 eV have spin 2 while those at 4.5, 35.8, 53.5, 58.9, 66.2, 68.9, 74.5, 96.4, 145.3, and 168.8 have spin 3. The interesting feature of these findings is that all the spin 2 resonances in this neutron energy interval have reduced neutron widths larger than the average value.

In order to compare the present experimental results with predictions of nuclear models, the absolute intensities have to be determined. This was arrived at by normalizing the intensity of the γ ray, due to neutron capture in the 4.5 eV resonance and populating the excited state of ^{174}Yb at 76.5 keV, to a value of 26.5±0.6 photons per 10^3 captures. This value is obtained by normalizing Carpenter's[71] ^{173}Yb results to the recent Pt standard determined by Wasson. The absolute γ ray intensities for resolved J = 2 resonances and E1 transitions are summarized in Table 1. For comparison, the intensities due to neutron capture in the 4.5 and 35.8 eV resonances (J = 3) are included.

Next let us closely examine the γ ray spectra due to neutron capture in the neutron resonances at 17.7, 31.5, 35.8, and 45.3 eV. Inspection of Figure 12 reveals striking regularities in the γ ray spectra of these resonances.

1. The first aspect of the data is the qualitative similarity of the spectra:

   (a) The rotational band based on the ground state is weakly populated in the (n,γ) data of these resonances as well as in the (d,p) data.

   (b) There is a clustering of γ ray strength in a γ ray energy interval $5730 \leq E_\gamma \leq 5839$ which corresponds to the γ vibrational band and the $k^\pi = 1^+$ band. Peaks labelled by 9, 12, and 16 correspond to three members of the γ-vibrational band while peaks 8, 10, and 14 correspond to three members of the $k^\pi = 1^+$ band. Of particular interest is that the γ ray labelled 8 appears relatively strongly in the spectra of the J = 2 resonances but not in the spectra of the J = 3 resonances. This indicates that the spin of this final state at E_x = 1624 keV is 1^+. Reich, et al.[72] tentatively proposed that this is $k^\pi = 1^+$ band head and that the major component of this level is possibly the two quasiparticle state $7/2^-[514] - 5/2^-[512]$. Also one notes that the γ-vibrational band is strongly populated in the (d,p) reaction.

2. An unusual concentration of γ ray strength in a small γ ray energy interval in the spectrum of the 17.7 eV resonance. These are indicated by lines 56 - 67 in Figure 12. What is equally surprising is the fact that the intensity of these γ rays is about equally the same.

TABLE 1

Measured absolute γ ray intensities due to neutron capture in individual resonances of ^{173}Yb. The absolute values have been determined by normalizing the 7389.7 keV γ ray of the 4.5 eV resonance to a value of 26.5±0.6 photons per 10^3 captures (see text). At the bottom of the Table ratios of γ rays pertaining to the γ vibrational and $k^\pi = 1^+$ bands are considered.

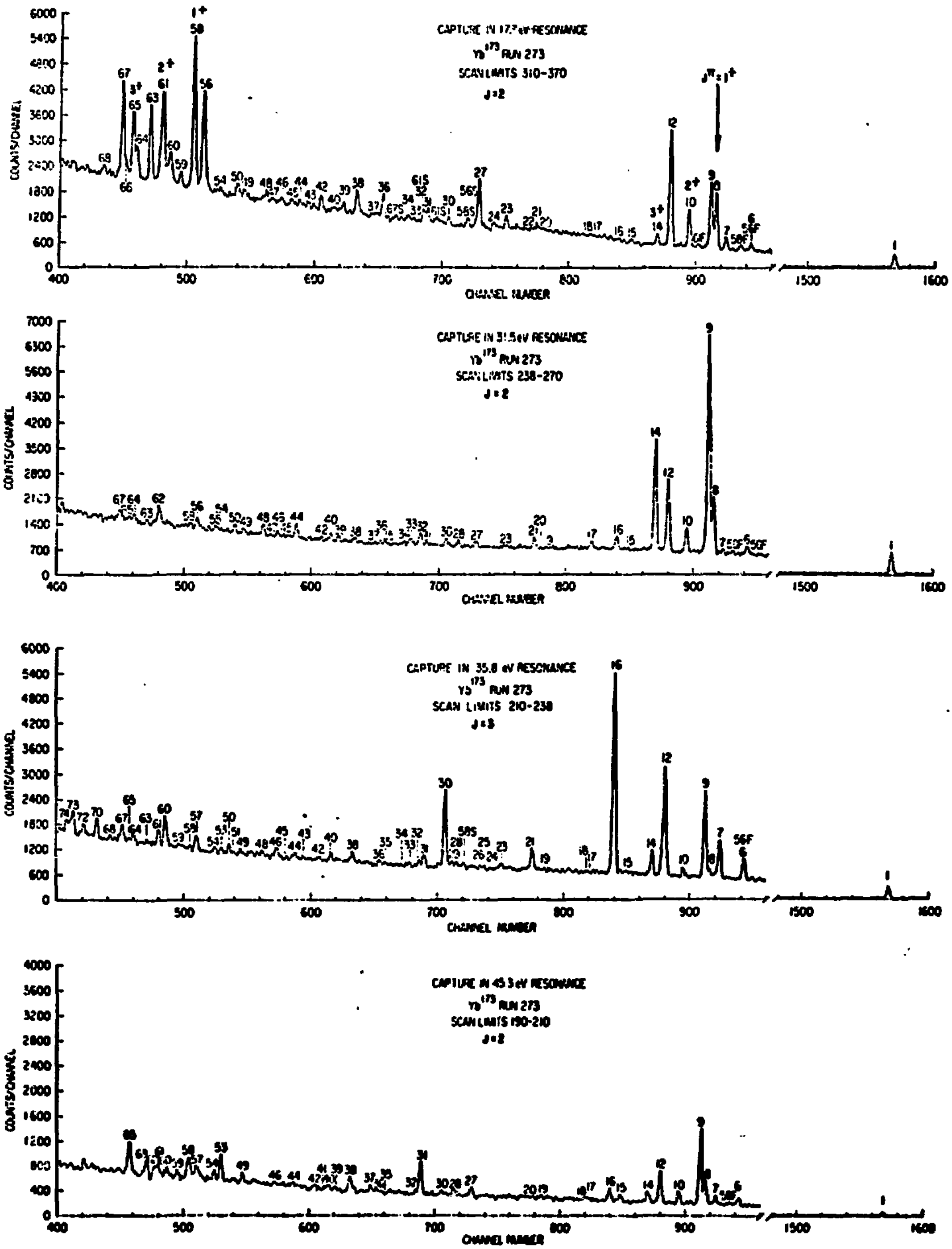
$^{173}Yb(n,\gamma)^{174}Yb$

Absolute γ Ray Intensities

E_o(eV) →			4.5	17.7	31.5	35.8	45.3	105.9
E_γ(keV) :	J^π	K^π	I_γ (Photons/1000 Capture)					
7389.7	2^+	0^+	26.5±0.6	2.9 ±0.2	7.1±0.3	3.5 ±0.2	1.4±0.2	1.1±0.6
7211.0	4^+	0^+	24.9±0.7	---	---	0.2 ±0.2	---	---
5903.3	2^+	0^+	8.5±0.4	0.1 ±0.1	2.0±0.3	4.4 ±0.7	1.8±0.3	18.1±2.4
5857.8	3^+	3^+	3.6±0.3	1.7 ±0.1	0.5±0.1	8.4 ±0.5	1.9±0.3	5.6±1.1
5839.4	1^+	1^+	---	7.7 ±0.3	10.6±0.4	---	6.7±0.4	7.8±1.3
5829.8	2^+	2^+	2.6±0.2	9.7 ±0.3	44.6±0.9	17.0 ±0.8	20.5±0.7	7.1±1.3
5789.1	2^+	1^+	0.7±0.2	5.5 ±0.2	4.7±0.3	1.8 ±0.4	3.7±0.4	1.7±0.8
5763.1	4^+	3^+	0.6±0.2	---	---	---	---	---
5754.4	3^+	2^+	0.2±0.2	16.6 ±0.4	14.7±0.5	23.1 ±1.1	8.8±0.6	2.7±1.4
5749.1	4^+	0^+	5.5±0.5	---	---	5.0 ±2.0	---	---
5730.0	3^+	1^+	1.0±0.2	1.6 ±0.2	22.3±0.6	4.9 ±0.6	3.4±0.4	3.5±1.7
5658.6	4^+	2^+	0.6±0.2	---	---	42.2 ±1.7	4.0±0.4	---
5605.4	4^+	1^+	9.1±0.7	9.1 ±0.7	---	---	0.2±0.2	---
5505.5	2^+	0^+	0.2±0.2	0.3 ±0.1	2.5±0.3	4.5 ±0.4	0.2±0.2	0.4±0.4
R(5839/5789)				1.4 ±0.1	2.3±0.1		1.8±0.2	4.6±2.5
R(5830/5754)				0.58±0.02	3.0±0.1	0.74±0.05	2.3±0.2	2.6±1.4

Figure 12

Capture γ ray spectra of strong s-wave resonances in ^{173}Yb. Note the clustering of γ ray strength in γ ray energy region denoted by lines 7 to 16. A second concentration of γ ray strength is shown in the 17.7 eV resonance.



Furthermore, at a glance one can note certain regularities in the spectra of the resonances with $J = 2$. As an illustration, the ratio of the γ ray intensities of peaks 8 and 10 (two numbers of the $k^{\pi} = 1^{+}$ band, see Table 1 also) does not fluctuate strongly from one resonance to another. These observations point to nonstatistical effects in the reaction mechanism of $^{173}Yb(n,\gamma)^{174}Yb$. A quantitive measure of this effect can be arrived at by studying the correlation coefficient between $\Gamma_{\gamma if}$ and Γ^{0}_{ni} by using a Monte Carlo method which takes into account the limited sample size. The results of the analysis for $J = 2$ resonances are summarized in Figure 13.

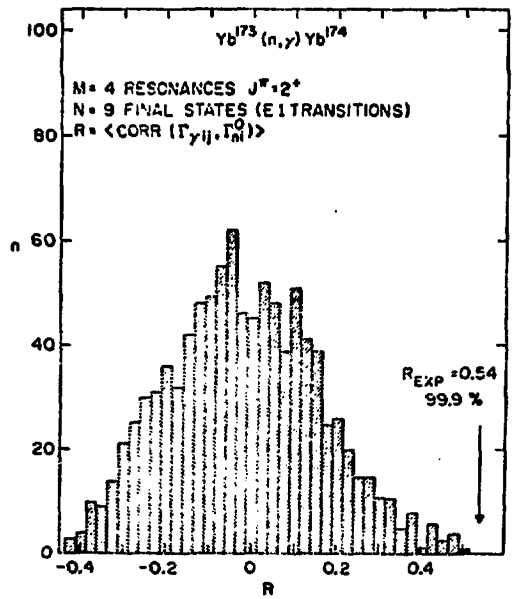


Figure 13

A correlation coefficient, $\rho = 0.54$, indicates in Lane's picture, that there are 2 doorway states. In Soloviev's picture this indicates that there are 2 dominating components in the wave function of the highly excited neutron resonance states.

As shown an experimental value $\rho = 0.54$ is obtained, which when compared with a Monte Carlo calculation, shows that its confidence limit is 99.8%. Similar calculations carried out for resonances with spin 3 show that $\rho = 0.29$. The results are summarized in Table 2.

Table 2

^{173}Yb Correlation Coefficients

ρ	No. of Resonances and Spin	No. of γ Rays and Spin	Confidence Factor
0.54	4(J^{π}= 2)	8(J^{π}= 1^{+},2^{+},3^{+})	99.8%
0.29	9(J^{π}= 3^{-})	12(J^{π}= 2^{+},3^{+},4^{+})	98.0%

A comparison of the (n,γ) and (d,p) data shows qualitatively that the two are correlated; unfortunatly the (d,p) data is not of high enough resolution to determine whether the members of the $k^{\pi} = 1^+$ band are strongly populated in the (d,p) reaction. It is interesting to point out that in this mass region Fubini, et al. reports a correlation coefficient between thermal (n,γ) reduced intensities and (d,p) spectroscopic factors, $\rho = 0.42$ for ten final states in ^{177}Lu.(73)

These aspects of the data give indications of valence neutron capture. However, there are two difficulties with this interpretation: (1) the absolute magnitudes of the predictions are small when compared with the experimental results, and (2) the proposed structure of the γ-vibrational band and the $k^{\pi} = 1^+$ band is not favorable for valence neutron capture. In view of these considerations, we invoke a doorway state reaction mechanism to explain the present ^{173}Yb results.

In recent years, Lane formulated a theory for a description of the correlation coefficients in this mass region in terms of doorway states. A parallel development in terms of doorway states was also advanced by Beer.(74) An alternative approach was adopted by Soloviev(75) in which he described the highly excited resonant states by the quasiparticle components.

In Lane's picture, the present correlation coefficients indicate that there are 4 doorway states with $J^{\pi} = 3^+$ and about 2 doorway states with $J^{\pi} = 2^+$. Furthermore, the distribution of the partial radiative widths were studied by the methods of relative variance and maximum likelihood. The summary of the results is contained in Table 3.

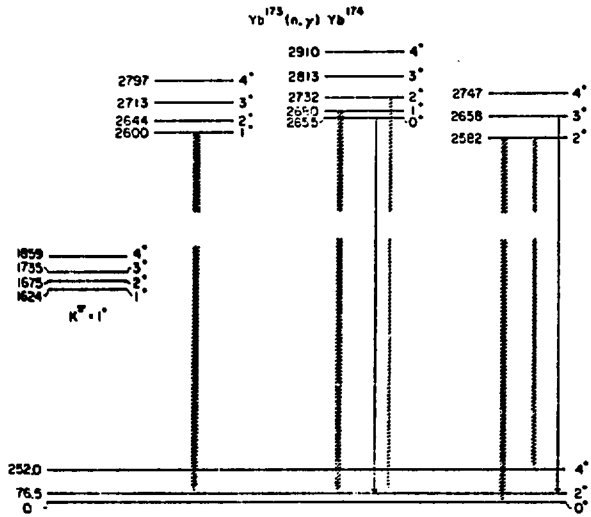
Table 3

Number of Degrees of Freedom, ν

Resonance Spins	Maximum Likelihood	Relative Variance
2	$2.4^{+0.6}_{-0.7}$	$1.7^{+0.5}_{-0.5}$
3	$1.5^{+0.3}_{-0.3}$	$1.6^{+0.5}_{-0.4}$

Two possible sources which might tend to increase the value of ν are (1) unresolved levels, and (2) correlated γ rays. The latter interpretation is plausible (see Table 1) although the former could not be excluded.

Finally let us turn our attention to the second cluster of γ rays present in the spectrum of the 17.7 eV resonance. In order to shed further light on the ^{173}Yb reaction mechanism, it is necessary to determine the nuclear structure properties of these high-lying states. Unfortunatley this information was not available from the (d,p) or other reaction studies. An attempt was made to unravel the structure of these states by examination of the low energy γ rays at $E_x = 2600$ keV and by a comparison of the spectra of the resonances of spin 2^+ and 3^+. With the aid of this information and with appeal to the systematics of rotational level spacings,



TENTATIVE DECAY SCHEME OF EXCITED STATES AT Ex ≈ 2600 keV

Figure 14

Proposed decay scheme of the strong γ rays in the 17.7 eV resonance feeding excited states at $E_x \approx 2600$. Three bands with spins $k^{\pi} = 0^+, 1^+, 2^+$ are tentatively assigned. Also included in the Figure is the $k^{\pi} = 1^+$ band at $E_x = 1624$ proposed by Reich, et al. The excited state at $E_x = 2655$ keV is based on the observation of a low-energy γ ray.

$$\Delta E = \frac{\hbar^2}{2\mathcal{J}}[I(I+1) - I_o(I_o+1)]$$

it was possible to construct three bands which may be identified with $k^\pi = 0^+$, 1^+, and 2^+ and band heads at E_x = 2655(0^+), 2600(1^+), and 2582(2^+) respectively.

Coincidence experiments are required in order to establish these conclusions. The interesting feature of these investigations is that the rotational inertial parameter $\hbar^2/2\mathcal{J}$ derived for these states is not significantly different from those of the low lying states. What is perhaps more surprising is that at such high excitation energies, there possibly exist well behaved bands. In recent years a great deal of theoretical and experimental interest is exhibitted in the study of the $k^\pi = 1^+$ bands. Two theoretical views(75) are that the structure of these bands may be either collective or may be due to two-quasiparticle excitations. In terms of the latter description, a possible candidate for the $k^\pi = 1^+$ band is the two neutron quasiparticle state $5/2^-$[512] - $3/2^-$[512]. At higher mass numbers, because the single particle neutron state is bound, the expectations are that correlations between partial radiative widths and reduced neutron widths and/or (d,p) spectroscopic factors must vanish.(77) However, correlations between a pair of γ rays may still persist.(74) These views seem to be consistent with the present available experimental data.

In conclusion, I hope that I have conveyed to you some of the excitment and the large wealth of data that can be derived in the study of the reaction mechanisms in radiative neutron capture. The present available data indicate that departures from the extreme statistical model can not be regarded as a statistical fluctuation but as a reality which is due to (1) the influence of single particle effects and doorway state contribution and (2) simple structural components in the capturing states. Further experimental and theoretical investigations are required in order to shed additional light on this interesting problem.

I am gratefully indebted to Dr. H. Palevsky, without whose encouragement and help the present study would have not been possible; and to Dr. A. M. Lane for his interest, stimulating correspondence and discussions. I would like to thank Drs. C. W. Reich and R. C Greenwood for making the average capture results of ^{171}Yb and ^{173}Yb available prior to publication.

Most of the investigations reported here are the results of the combined experimental efforts of the BNL fast chopper group (Drs. R. E. Chrien, O. A. Wasson, A. W. Cole, M. R. Bhat, and S. F. Mughabghab), the BNL monochromator group (Drs. W. R. Kane and R. F. Casten), and the ORNL Linac group (Drs. G. G. Slaughter and J A. Harvey). It is a great pleasure to acknowledge the help and assistance of Dr. G. A. Barthalomew of Chalk River during his 1971 summer visit to Brookhaven National Laboratory.

References

1. E Fermi, E. Amaldi, O. D'Agostino, F. Rasetti, and E. Segré, Proc. Royal Soc. (London) A 146, 483 (1934).

2. N. Bohr, Nature 137, 344 (1936).

3. A. M. Lane and J. E. Lynn, Nucl. Phys. 17, 586 (1960).

4. J. E. Lynn, The Theory of Neutron Resonance Reactions (Clarendon, Oxford, England, 1968) 330.

5. A. M. Lane, Statistical Properties of Nuclei, (Plenum Press, N.Y., 1972) Edited by J. B. Garg, p. 271.

6. S. Fallieros, Private Communication.

7. T. Teichman and E. P. Wigner, Phys. Rev. 87, 123 (1952).

8. G. E. Brown, Nucl. Phys. 57, 339 (1964).

9. L. Estrada and H. Feshbach, Ann. Phys. 23, 123 (1963).

10. G. A. Bartholomew, E. D. Earl, A. J. Ferguson, and I. Bergqvist, Can. J. Phys. 48, 687 (1970). See Also G. A. Bartholomew, Studsvik Conference (IAEA, Vienna 1969) p. 553.

11. R. E Chrien, K. Rimawi, and J. B. Garg, Phys. Rev. C3, 2054 (1971).

12. C. E. Porter, and R. G. Thomos, Phys. Rev. 104, 483 (1956).

13. C. E Porter and N. Rosenzweig, Suomalaisen Tiedeakatemian Toimituksia (Ann. Acad. Sci. Fennicae) AVI, No. 44 (1960).

14. L. M. Bollinger, Experimental Neutron Resonance Spectroscopy, Editor J. A. Harvey (Academic Press, N.Y. 1970) p. 235 and references therein.

15. O. A. Wasson, R. E. Chrien, G. G. Slaughter, and J. A. Harvey, Phys. Rev. C3, 900 (1971).

16. L. M. Bollinger and G. E. Thomas, Phys. Rev. C2, 1951 (1970).

17. M. A. Mariscotti, J. A. Moragues, W. Gelletly, and W. Kane, Phys. Rev. Letters 22, 1303 (1969).

18. O. A. Wasson, M. R. Bhat, R. E. Chrien, M. A. Lone, and M. Beer, Phys. Letters, 25B, 195 (1967).

20. F. Becvar, R. E. Chrien, and O. A. Wasson, Bull. Am. Phys. Soc. 15, 1667 (1970).

21. R. Moreh and A. Wolf, Neutron Capture Gamma Ray Spectroscopy, (IAEA, Vienna, 1969) p. 483.

22. L. V. Groshev and A. M. Demidov, Yadernaya Fiz. 4, 785 (1966).

23. S. E. Arnell, R. Hardell, Ö. Skeppstedt, and E. Wallender, Neutron Capture Gamma-Ray Spectroscopy, (IAEA, Vienna, 1969) p. 231.

24. S. Cochavi and W. R. Kane, Private communication.

25. S. E. Arnell, R. Hardell, A. Hasselgren, C. G. Mattsson, and Ö. Skeppstedt, Physica Scripta 4, 89 (1971).

26. S. F. Mughabghab, Physics Letters 35B, 469 (1971).

27. E. G. Bilpuch, K. K. Seth, C. D. Bowman, R. H. Tabony, R. C. Smith, and H. W. Newson, Ann. Phys. (New York) 14, 387 (1961).

28. J. B. Garg, J. Rainwater, and W. W. Havens, Jr., Phys. Rev. 3C, 2447 (1971).

29. S. F. Mughabghab, Third Neutron Cross Section and Technology Conference (Knoxville, Tennessee, March 1971) 1, 386.

30. L. N. Bystrov, Z. A. Rudak, E. T. Firsov, 16th All Union Conference of Nuclear Spectroscopy and Structure of Atomic Nuclei, Moscow, p. 19 (1966), as reported in Nuclear Data 3, Section A, No. 4-6 (1967), Ed. K. Way.

31. A. F. Gamalii, B. V. Zemtsev, V. B. Ivanov, B. V. Nesterov, and L. P. Kam'yanov, Yadernaya Fizika 15, 3 (1972).

32. R. C. Block, Private communication.

33. H. E. Jackson and E. N. Strait, Phys. Rev. 4C, 1314 (1971).

34. M. R. Bhat, R. E. Chrien, S. F. Mughabghab, and O. A. Wasson, Contribution 4.1 to International Conference on Statistical Properties of Nuclei (August 1971, Albany, N. Y.).

35. H. E. Jackson and E. N. Strait, Phys. Rev. Letters 27, 1654 (1971).

36. R. C. Block, R. G. Stieglitz, and R. W. Hockenbury, Third Neutron Cross Section and Technology Conference (Knoxville, Tennessee, 1971) p. 889. See also Stieglitz, R. W. Hockenbury, and R. C. Block, Nucl. Phys. A163, 592 (1971).

36a. Note added in Proof: Recently F. Froehner, H. Beer, R. R. Spencer and A. Ernst have made their total radiative width measurements of ^{47}Ti, ^{50,52,53}Cr, ^{54,56,57}Fe, ^{58,60,61,62}Ni available to us. There seems to be a small positive correlation for the even Cr isotopes and for ^{60}Ni. It is interesting to note that the overall sample of 67 measured radiative widths shows a correlation coefficient 0.18±0.03. See contribution D4 to this conference.

37. R. C. Diehl, B. L. Cohen, R. A. Moyer, and H. L. Goldman, Phys. Rev. 1C, 2132 (1970), and references therein.

38. S. F. Mughabghab, R. E. Chrien, O. A. Wasson, and M. R. Bhat, Bull. Am. Phys. Soc. 15, 1667 (1970).

39. G. Rohr, H. Weigmann, and J. Winter, Nucl. Phys. A150, 97 (1970).

40. S. F. Mughabghab, O. A. Wasson, G. W. Cole, and R. E. Chrien, Third Neutron Cross Section and Technology Conference (Knoxville, Tennessee, 1971), 2, 804 and 808. See also M. R. Bhat, R. E. Chrien, G. W. Cole, S. F. Mughabghab, and O. A. Wasson, Contribution A30 to this conference.

41. S. F. Mughabghab, R. E. Chrien, O. A. Wasson, G. W. Cole, and M. R. Bhat, Phys. Rev. Letters 26, 1118 (1971).

42. R. E. Chrien, Statistical Properties of Nuclei, Edited by J. B. Garg, (Plenum Press, New York 1972), p. 233.

43. W. R. Kane, Private communication.

44. H. Weigmann, G. Rohr, and J. Winter, Third Neutron Cross Section and Technology Conference, (Knoxville, Tennessee, 1971) 2, 749.

45. J. A. Harvey, et al., Private communication.

46. S. F. Mughabghab, Statistical Properties of Nuclei, Edited by J. B. Garg, (Plenum Press, New York, 1972), p. 291.

47. O. A. Wasson and G. G. Slaughter, Contribution D6 to this Conference and Private communication.

48. K. Rimawi, Dissertation (State University of New York at Albany, August 1969).

49. S. F. Mughabghab, G. W. Cole, R. E. Chrien, M. R. Bhat, O. A. Wasson, and G. G. Slaughter, Bull. Am. Phys. Soc. 17, 16 (1972).

50. S. F. Mughabghab, W. R. Kane, and R. F. Casten, Contribution D2 to this Conference.

51. R. C. Diehl, B. L. Cohen, R. A. Moyer, and L. H. Goldman, Phys. Rev. 1C, 2086 (1970).

52. B. L. Cohen, R. A. Moyer, J. B. Moorehead, L. H. Goldman, and R. C. Diehl, Phys. Rev. 176, 140 (1968).

53. M. R. Bhat, G. W. Cole, O. A. Wasson, R. E. Chrien, and S. F. Mughabghab, Bull. Am. Phys. Soc. 17, 17 (1972).

54. S. F. Mughabghab, G. W. Cole, R. E. Chrien, O. A. Wasson, and M. R. Bhat, Bull. Am. Phys. Soc. 17, 557 (1972).

55. H. Tellier, M. Alix, and J. Dabbs, Saclay Report, CEA-N-1268 (1970).

56. R. E. Coté, Private communication through G. E. Thomas.

57. P. Axel, Phys. Rev. 126, 671 (1962).

58. B. W. Thomas, Statistical Properties of Nuclei, Edited by J. B. Garg, (Plenum Press, New York 1972), p. 251.

59. S. F. Mughabghab, R. E. Chrien, and O. A. Wasson, Phys. Rev. Letters 25, 1670 (1970).

60. G. G. Slaughter, O. A. Wasson, S. F. Mughabghab, R. E. Chrien, G. W. Cole, and M. R. Bhat, Bull. Am. Phys. Soc. 17, 580 (1972). See also S. F. Mughabghab, et al., Contribution D2 to this conference.

61. L. S. Danelyan, A. M. Demidov, S. V. Krupin, S. K. Sotnikov, A. Zarandi, B. Kardon, L. Szabo, and Z. Seres, JETP 62, 4, 25 (1972).

62. G. W. Cole, S. F. Mughabghab, and R. E. Chrien, contribution D8 to this conference.

63. A. M. Lane, Ann. Phys. (New York) 63, 171 (1971), and A. M. Lane, Physics Letters 31B, 344 (1970).

64. S. F. Mughabghab and R. E. Chrien, Phys. Rev. 1C, 1850 (1970).

65. O. W. B. Shult, et al., Phys. Rev. 154, 1146 (1967).

66. S. F. Mughabghab, O. A. Wasson, G. W. Cole, R. E. Chrien, and M. R. Bhat, Bull. Am. Phys. Soc. 16, 496 (1971).

67. H. Liou, Private communication.

68. S. F. Mughabghab and R. E. Chrien, Phys. Rev. 174, 1400 (1968).

69. D. R. Bès, P. Federman, E. Maqueda, and A. Zuker, Nucl. Phys. 65, 1 (1965).

70. D. G. Burke and B. Elbeck, Mat. Fys. Medd. Dan. Vid. Selsk. 36, 6 (1967).

71. R. T. Carpenter, ANL-6589 (1962).

72. R. C. Reich and R. C. Greenwood, Private communication.

73. A. Fubini and D. Prosperi, Contribution D9 to this conference.

74. M. Beer, Ann. Phys. (New York) 65, 181 (1971).

75. V. G. Soloviev, Physics Letters 35B, 109 (1971).
V. G. Soloviev, ibid, 36B, 199 (1971).

76. I. Hamamoto, Nucl. Phys. A177, 484 (1971).

77. E. D. Earle, M. A. Lone, G. A. Bartholomew, B. J. Allen, G. G. Slaughter, and J. A. Harvey, Statistical Properties of Nuclei, Edited by J. B. Garg, (Plenum Press, 1972), p. 263.