cidence rate about 10^4 times smaller than the observed rate. Among the pure γ-ray emitting level assignments again 2^- is most consistent with the observed results, although 3^+ cannot be ruled out.

In summary, the decay schemes for the levels fed by the inelastic proton groups giving strong p-γ coincidences are indicated in Fig. 10.

There is some indication that the comparatively weak group VI leading to a level in O^{16} at 12.02 ± 0.03 Mev, is probably accompanied by γ-ray emission (refer to Fig. 8 and refer to Fig. 5 for the relative yield at $\theta_{lab} = 150°$, the angle of observation in the coincidence runs).

VI. CONCLUSION

Three levels in O^{16} which have not been observed in the α-C^{12} scattering experiments appear in the inelastic scattering of 19-Mev protons by O^{16}. The levels at 8.87- and 11.08-Mev decay by γ emission; the characteristics of the decay suggest that these levels are 2^- states. The decay of the level at 12.02 Mev is probably accompanied by γ emission.

The present investigation was undertaken in order to locate the negative-parity members of the $2^{\pm}$ doublets predicted by the α-particle model of Dennison.[3] The energy splitting is expected to be small with the 2^- level shifted, if at all, to higher energies.[3,13] Under scheme (a) of Dennison[3] we might have expected to find γ-emitting levels close to 9.83, 11.51 and 12.95 Mev; while under scheme (b) the 2^- members are at 6.9, 9.83, 11.51 and 12.51 Mev. With the obvious exception of the 6.9-Mev level, there is no correspondence in either case with our observed γ-emitting states. Thus the present results do not lend support to this α-particle model. It should be noted that this model does not predict isolated 2^- states. If our present assignments to the levels at 8.87 and 11.08 Mev are correct and further measurements do not uncover 2^+ states close to these (there is the uncertain level at 11.10 Mev[1]), one must view these levels from the standpoint of other nuclear models (see reference 13).

The authors wish to express their thanks to S. Berko of the University of Virginia for his assistance in the development of the coincidence circuit used in this experiment, to G. Likely and G. Schrank for the use of some of their experimental equipment and to W. Stone for his able assistance. This research was stimulated by conversations with H. T. Richards and W. A. Fowler on the level structure of O^{16}.

[13] D. R. Inglis, Revs. Modern Phys. **25**, 390 (1953).

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Radiation Widths in Slow Neutron Resonances*

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A summary of current measurements of total radiation widths as observed in slow neutron resonance capture is presented together with the most recent data for a number of resonances in iridium, lutetium, and tungsten.

The general features of the dependence of radiation width upon atomic weight is discussed in terms of a model proposed by Blatt and Weisskopf.

INTRODUCTION

It is possible to study the virtual excited states of heavy nuclei near the neutron binding energy by means of the measurements of total and scattering neutron resonance cross sections. For slow neutrons the predominate mode of decay of these virtual states is by gamma-ray emission. Analysis of the cross sections for the Breit-Wigner resonance parameters yields directly a measure of the radiation width or lifetime of the excited states for de-excitation by gamma emission, a parameter which depends sensitively on the wavefunctions of these states. Because of this dependence, significant information regarding nuclear wave functions should be obtained from a comparison of experimental gamma-decay transition probabilities with theoretical values calculated on the basis of specific models of the nucleus.

The development and success of the nuclear shell model led Weisskopf[1] to estimate the matrix elements for electric and magnetic multipole transitions of a single nucleon which moves independently within the nucleus. Goldhaber and Sunyar[2] have examined the isomeric transitions for low-lying states in medium and heavy nuclides in terms of these estimates. In light nuclei Wilkinson[3] has made comparison with these estimates for highly excited states. They have found that

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[1] V. F. Weisskopf, Phys. Rev. **83**, 1073 (1951).
[2] M. Goldhaber and A. W. Sunyar, Phys. Rev. **83**, 906 (1951).
[3] D. H. Wilkinson, Phil. Mag. **44**, 450 (1953).

for many of the transitions of definite multipole order between states of known character Weisskopf's formulas predict the correct functional dependence on energy and nuclear radius as well as the correct order of magnitude for the transition rate. Sunyar[4] has shown, however, that for many transitions in nuclei which are intermediate to closed shells a "cooperative" type of transition is involved in which the collective aspects of nuclear motion are combined with that of the individual particle.

For emission by highly excited states where the wave functions should no longer be single-particle, Blatt and Weisskopf[5] have modified the single-particle formulas to take into account the complexity of the emitting state. A retardation of the radiative process by a factor directly proportional to the level spacing of states which can combine with the emitting state by a specified multipole transition is predicted. Kinsey and Bartholomew[6] have studied the partial radiation widths for just such states which are excited by slow neutron capture and have interpreted their results in terms of these modified equations. They have concluded that the predicted retardation is accounted for in the elements they have been able to study over a wide range of level spacings, although the absolute rates of emission are an order of magnitude lower than calculated.

A number of attempts[7] have been made to combine these estimates of the transition probabilities with a statistical model of nuclear level spacing to evaluate[8] the

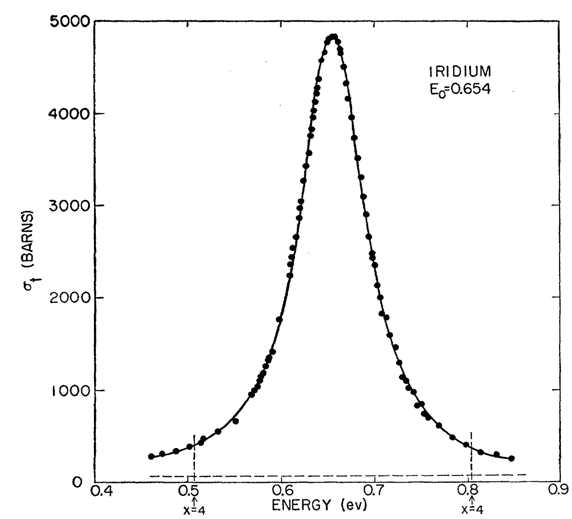

FIG. 1. Total neutron cross section of elemental iridium in the vicinity of the 0.654-ev resonance.

[4] A. W. Sunyar, Phys. Rev. 98, 653 (1955).
[5] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952), Chap. XII.
[6] B. B. Kinsey and G. A. Bartholomew, Phys. Rev. 93, 1260 (1954).
[7] C. L. Critchfield (unpublished); B. B. Kinsey, in *Beta and Gamma Ray Spectroscopy*, edited by Kai Siegbahn (Interscience Publishers Inc., New York, 1955), Chap. XXV; J. S. Levin and D. J. Hughes, Phys. Rev. 98, 1161 (1955); see also J. S. Levin, thesis, Cornell University, 1955 (unpublished).
[8] See Blatt and Weisskopf, reference 5, p. 649, Eq. (7.23).

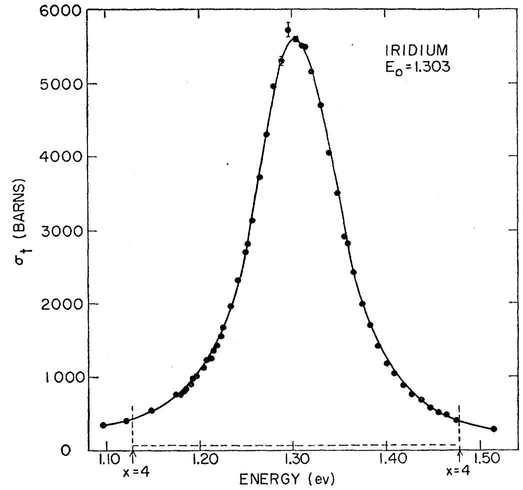

FIG. 2. Total neutron cross section of elemental iridium in the vicinity of the 1.303-ev resonance.

total radiation width to be observed from a highly excited state emitting a multiplicity of gamma rays to lower lying states. Total radiation widths, however, have been known for some time to be remarkably constant in the region of heavy nuclei. It is only when precise measurements have been made that such calculations can be compared with experiment with confidence. It has been the program of the BNL crystal spectrometer group to accumulate as many such measurements as possible to a precision which will permit significant variations to be observed. In this paper are presented our latest measurements as well as those values which are currently known to an accuracy of approximately 15 percent or better.

MEASUREMENTS

The details of total cross-section measurements with the BNL crystal spectrometer have been published[9] previously. The total cross section for iridium has been remeasured with our best resolution up to 10 ev and previously up to ~30 ev with poorer resolution. Four metallic iridium foils of approximately 0.001 inch thickness were used separately or together depending on the cross-section to be measured. The results for the 0.654, 1.303, and 5.36 ev resonances are shown in Fig. 1, Fig. 2, and Fig. 3 respectively. Previous measurements on iridium were made by Sturm,[10] Rainwater *et al.*,[11] Sawyer *et al.*,[12] and Christensen.[13] Activation measurements on these three resonances were also made in order to assign the resonances isotopically. The 0.654-ev and 5.36-ev resonances are most probably in Ir^{191} since no 19-hr activity was found after irradiation in the monochro-

[9] L. B. Borst and V. L. Sailor, Rev. Sci. Instr. 24, 141 (1953).
[10] W. J. Sturm, Phys. Rev. 71, 757 (1947).
[11] Rainwater, Havens, Wu, and Dunning, Phys. Rev. 71, 65 (1947).
[12] Sawyer, Wollan, Bernstein, and Peterson, Phys. Rev. 72, 109 (1947).
[13] R. L. Christensen and V. L. Sailor (unpublished).

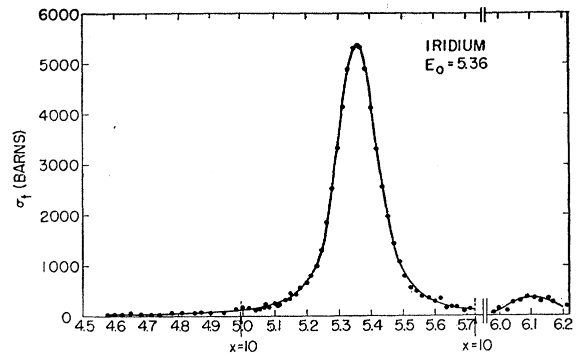

FIG. 3. Total neutron cross-section of elemental iridium in the vicinity of the 5.36- and 6.1-ev resonances.

matic diffracted beam of the spectrometer. The assignment of the 1.303-ev resonance to Ir^{193} by Goldhaber *et al.*[14] has been confirmed. In addition to these resonances others were observed at 6.1, 9.03, and 9.9 ev with one or more being grouped at 19.5, 25.5, and 31 ev.[13] No attempt at the assignment of these resonances was made.

Two resonances in lutetium were rerun[15] using a special thick sample[16] of 20 g of Lu_2O_3 in dry powder form. The resulting cross-section curves for these and an additional resonance in tungsten have not been shown but will be submitted as data to be included in the next supplement to the neutron cross section compilation.[17] The statistical accuracy of the data is comparable to that shown for iridium. The 4.14-ev resonance[18] in W^{182} was run using metallic samples of the element ranging from 0.010 inch to 0.150 inch in thickness.

ANALYSIS AND RESULTS

The analysis of measured total cross-section data for single-level resonance parameters to the precision required for this study requires careful consideration of the role of Doppler and resolution effects. Previous discussion of the methods for treatment of these effects has been published.[19] Whenever possible we have chosen to apply shape analysis[19,20] to cross-section data, considering these methods to be the most likely to yield precision. When combined with area methods, in the best cases it is possible to achieve three essentially independent determinations of the total width parameter Γ. We have chosen to measure only those cases for which independent determinations are possible. For the present this means below approximately 10 ev. The limits of error quoted take into consideration the self-consistency of such independent determinations.

TABLE I. The single-level resonance parameters for three levels in iridium. The tabulated quantity, σ_0, is not corrected for isotopic abundance. The quantity, $g\Gamma_n$, is corrected for isotopic abundance.

E_0 (ev)	0.654±0.002	1.303±0.005	5.36±0.04
σ_0 (barns)	5290±100	6390±120	9200±500
Γ (ev)	0.074±0.001	0.0875±0.001	0.074±0.005
$g\Gamma_n$ (ev)	$(2.5\pm0.1)\times10^{-4}$	$(4.6\pm0.1)\times10^{-4}$	$(3.6\pm0.2)\times10^{-3}$
Γ_γ (ev)	0.0735±0.001	0.0865±0.001	0.067±0.005
$\sigma_0\Gamma$ (barns ev)	390±4	559±6	678±15

[14] Goldhaber, Yalow, Barbre, Lowry, and Sunyar, Brookhaven National Laboratory Report BNL-C-9, 96, 1949 (unpublished).
[15] Foote, Landon, and Sailor, Phys. Rev. **92**, 656 (1953).
[16] We are indebted to Dr. F. H. Spedding of the Ames Laboratory for the loan of this sample.
[17] D. J. Hughes and J. A. Harvey, *Neutron Cross Sections*, Brookhaven National Laboratory Report BNL-325. (Superintendent of Documents, U. S. Government Printing Office, Washington, D. C., 1955).
[18] W. Selove, Phys. Rev. **84**, 869 (1951).

The radiation width parameter Γ_γ is determined directly from the total width Γ by assuming the statistical weight factor $g=\frac{1}{2}$ in those cases in which it has not been determined. In no case does this lead to an error which is significant compared to the quoted errors.

The parameters which have resulted from the analysis of iridium, lutetium, and tungsten are quoted in Tables I, II, and III respectively. The parameters for the 5.36-ev resonance in iridium are somewhat less certain due to the lack of suitable measurements in the far wings of this resonance. A thicker sample than was available is required before these results can be improved. The Doppler effect is very large in the wings of this resonance and extremely careful measurements will be required.

TABLE II. The single-level resonance parameters for three levels in lutetium. The tabulated quantity, σ_0, is not corrected for isotopic abundance. The quantity, $g\Gamma_n$, is corrected for isotopic abundance.

E_0 (ev)	0.143±0.001	2.604±0.010	1.574±0.006
σ_0 (barns)	359±7	1970±40	207±20
Γ (ev)	0.061±0.002	0.059±0.001	0.055±0.005
$g\Gamma_n$ (ev)	4.6×10^{-5}	$(4.5\pm0.1)\times10^{-3}$	$(2.6\pm0.3)\times10^{-4}$ [a] $(6.9\pm0.7)\times10^{-6}$ [b]
Γ_γ (ev)	0.061±0.002	0.050±0.001	0.055±0.005
$\sigma_0\Gamma$ (barns ev)		116±1	11.2±0.2

[a] If Lu^{176}.
[b] If Lu^{175}.

The 1.57-ev resonance in lutetium is also a resonance for which analysis is difficult. The resonance is very weak and careful measurements with a very thick sample are needed in the wings before one can place confidence in results to a precision greater than quoted here.

The parameters for the 0.143-ev resonance have been obtained by a reanalysis of the data reported in reference 15. The resonance at 2.60 ev has been assigned to Lu^{176} on the basis of activation measurements and measured assymmetry in the resonance. It is only if it is in this rare isotope that it will show the typical interference shape of a strong resonance. There are therefore, two different radiation widths in Lu^{176} corresponding, most likely, to the two possible spin states.[19]

[19] H. H. Landon and V. L. Sailor, Phys. Rev. **98**, 1267 (1955); V. L. Sailor, Phys. Rev. **91**, 53 (1953).
[20] Wood, Landon, and Sailor, Phys. Rev. **98**, 639 (1955).

The 4.14-ev resonance in W^{182} is one of the few resonances in an even-even target nucleus for which accurate measurements have been possible.

A collection of those radiation widths which are known to a precision of approximately 15 percent or better is presented in Table IV. All of the values quoted, except for the one in U^{238}, have been measured by either a crystal spectrometer or slow chopper using "shape-type" analysis procedures, when possible. The tabulated values are shown plotted in Fig. 4.

DISCUSSION

Blatt and Weisskopf[5] have extended their modified independent-particle model estimate of the partial radiation width for transitions between highly excited states to evaluate, in approximate manner, the total width Γ_γ for such a state. Using a statistical model of the nucleus they have attempted to sum the partial widths of a highly excited state emitting gamma rays to many lower-lying states. They have assumed that the density of final states is given by an expression of the type $\rho(E)=c\exp(aE)^{\frac{1}{2}}$, where E is the excitation energy in the compound nucleus. The constants c and a are assumed to be slowly varying functions of the atomic weight and represent respectively the density of states at low excitation energy and the rate at which the density increases with energy. Admittedly, only very crude estimates are possible for these parameters at the present time, even if such a representation of the density of states is valid.

As the attempts[7] to compare these estimates with the current data have shown, the general features of the dependance of radiation width on atomic weight can be understood from such a model. As Fig. 4 very clearly shows, on the average there is a decrease of Γ_γ with increasing atomic weight A. This decrease is undoubtedly due to the decreasing neutron binding energy associated with increasing A, combined with decreasing level spacing at an energy of excitation of the compound nucleus corresponding to the binding energy. This later change in the level spacing corresponds to a change in both of the parameters c and a.

It is apparent in Fig. 4, however, that deviations from this general trend are certainly present. This is particularly evident in the region of atomic weight 208 if one examines the radiation widths for Au and the succeeding elements Hg, Tl, and Bi as reported by Levin and Hughes.[7] They have reported a deviation of a factor of 30 in this region. An attempt has been made by them to understand this in terms of the above model, inserting present empirical knowledge of level spacing and binding energy. A major difficulty is evident here, however, since a closing of both the neutron and proton shells leads to radical changes in the general trend of binding energies and level spacings.[21] Furthermore it has been observed by Kinsey and Bartholomew[22] that it is in just

TABLE III. The single-level resonance parameters for the 4.14-ev resonance in tungsten. The tabulated quantity, σ_0, is not corrected for isotopic abundance. The quantity, $g\Gamma_n$, is corrected for isotopic abundance.

E_0 (ev)	4.14 ± 0.03
σ_0 (barns)	5050 ± 200
Γ (ev)	0.047 ± 0.002
Γ_n (ev)	$(14.3\pm0.3)\times10^{-4}$ [a]
Γ_γ (ev)	0.046 ± 0.002
$\sigma_0\Gamma$ (ev barns)	236 ± 2

[a] $g=1$ since W^{182}.

TABLE IV. A summary of the most recently published radiation widths in the region of heavy nuclei. Only those values which are known to a precision of approximately 15 percent or better are tabulated.

Target	E_0 ev	Γ_γ (Mev)	Reference
$_{45}Rh^{103}$	1.260	155 ± 5	a
$_{47}Ag^{109}$	5.12	136 ± 6	b
$_{48}Cd^{113}$	0.178	113 ± 5	c
$_{49}In^{115}$	1.458	72 ± 2	d
	3.85	81 ± 4	d
$_{52}Te^{123}$	2.334	104 ± 3	e
$_{55}Cs^{133}$	5.90	115 ± 20	f
$_{54}Xe^{135}$	0.082	86 ± 11	g
$_{62}Sm^{149}$	0.096	64 ± 2	h
$_{63}Eu^{151}$	−0.0006	67	i
	0.327	70 ± 10	d
	0.461	93 ± 3	d
	1.056	94 ± 3	d
$_{64}Gd^{155}$	2.01	104 ± 5	j
$_{64}Gd^{157}$	2.82	114 ± 5	j
$_{70}Yb^{168}$	0.597	70 ± 5	k
$_{71}Lu^{176}$	0.142	61 ± 2	l
	2.604	50 ± 1	l
$_{72}Hf^{177}$	1.100	67 ± 2	m
	2.39	60 ± 1	m
$_{73}Ta^{181}$	4.28	49 ± 6	b
$_{74}W^{182}$	4.14	46 ± 2	l
$_{75}Re^{185}$	2.156	56 ± 1	n
$_{75}Re^{187}$	4.42	45 ± 1	n
$_{77}Ir^{191}$	0.654	73.5 ± 1	l
$_{77}Ir^{193}$	1.303	86.5 ± 1	l
$_{79}Au^{197}$	4.91	124 ± 3	o
$_{82}U^{235}$	...	29.5 ± 6	p
$_{82}U^{238}$	6.70	24 ± 2	q

[a] V. L. Sailor, Phys. Rev. **91**, 53 (1953).
[b] R. E. Wood, Phys. Rev. **95**, 644 (1954); see also, thesis, University of Utah, May 1955 (unpublished).
[c] B. N. Brockhouse, Can. J. Phys. **31**, 432 (1953).
[d] H. H. Landon and V. L. Sailor, Phys. Rev. **98**, 1267 (1955).
[e] H. L. Foote, Jr., Phys. Rev. **94**, 790 (1954).
[f] H. H. Landon and V. L. Sailor, Phys. Rev. **93**, 1030 (1954).
[g] See Seymour Bernstein and E. C. Smith, Proceedings of International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955 (to be published) for a summary of the most recent results for Xe^{135}.
[h] A. W. McReynolds and E. Anderson, Phys. Rev. **93**, 195 (1954); and V. L. Sailor (unpublished). The error given is assigned by the present author and takes into consideration a slight discrepancy which still exists between the quoted independent measurements.
[i] N. Holt, Phys. Rev. **98**, 1162 (1955).
[j] E. T. Florance and V. L. Sailor (private communication).
[k] Sailor, Landon, and Foote, Phys. Rev. **96**, 1014 (1954), and unpublished data.
[l] Reported in this paper.
[m] G. Igo and H. H. Landon (to be published).
[n] G. Igo, Phys. Rev. **100**, 1338 (1955).
[o] Wood, Landon, and Sailor, Phys. Rev. **98**, 639 (1955).
[p] Average value for a number of resonances, see V. L. Sailor, Proceedings of International Conference on Peaceful Uses of Atomic Energy, Geneva, 1955 (to be published).
[q] Bollinger, Dohlberg, Cote, Jackson, and Thomas, Phys. Rev. **98**, 223 (1955); R. S. Carter, Phys. Rev. **98**, 1161 (1955); see also D. J. Hughes and J. A. Harvey, *Neutron Cross Sections* Brookhaven National Laboratory Report BNL 325 (Superintendent of Documents, U. S. Government Printing Office, Washington, D. C., 1955).

[21] Hughes, Garth, and Levin, Phys. Rev. **91**, 1423 (1953).
[22] B. B. Kinsey and G. A. Bartholomew, Can. J. Phys. **31**, 1051 (1953); G. A. Bartholomew and B. B. Kinsey, Can. J. Phys. **31**, 1025 (1953); see also Kinsey, reference 7, for a discussion of just this point.

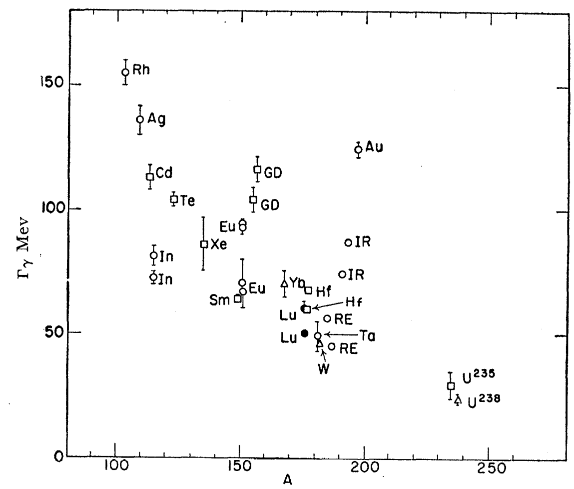

FIG. 4. Radiation width Γ_γ *versus* atomic weight A in the region of heavy nuclides. Only those values which are currently known to a precision of approximately 15 percent or better are plotted. The symbols ○, □, △, and ● indicate odd-even, even-odd, even-even, and odd-odd target nuclei respectively. The limits of error are not indicated when they are smaller than the symbol of indication.

this region of A that the capture gamma-ray spectra show a definite anomaly. The general spectrum[5] one would expect from the statistical model is clearly not observed, but rather an excessive number of high-energy transitions appear. This is most evident when one examines spectra from Pb^{207} and Pb^{208} in which essentially only single ground-state transitions are observed.[23] The statistical model should probably not be used in this region therefore.

An attempt has been made to apply the model to a few carefully chosen examples where more confidence might be felt in the results. Pairs of nuclei which differ by only two neutrons such as Ir^{191}, Ir^{193} and Re^{185}, Re^{187} were chosen. The even-even compound nuclei of Sm^{150}, $Gd^{156,158}$, and Hf^{178} were also chosen since knowledge about the trend of the spacing of the first excited states in such even-even nuclei is available.[24] It is difficult to be exact quantitatively with our still limited knowledge of the empirical constants which enter, but it is clear that the model does not predict an increase in the width in going from Ir^{191} to Ir^{193}. It is also clear that the widths in $Gd^{156,158}$ are too large compared with Hf^{178} unless a difference in the spin of the capturing state is important. Comparison of $Gd^{156,158}$ with Sm^{150} rules out this possibility, since capture in these nuclei must occur in the same or nearly the same spin state. There does not appear to be an explanation within the model for the large widths of Gd. The capture gamma-ray spectrum for this element does not show an abnormal number of high-energy transitions.[23] The gamma-ray multiplicity has been measured by Muehlhause[25] and found to be 3.9 which is also normal for this region of atomic weights.

Finally Xe^{136} is interesting in that its width appears normal in spite of the fact that it contains a magic number of neutrons and is known to show a large spacing of the first excited state.[24]

It appears, therefore, that the statistical model is not adequate to explain all of the observed deviations from the general trend of radiation widths. This conclusion is strengthened when one considers that there is evidence that within a single nuclide the radiation width shows measurably different values depending upon the resonant state in which the neutron is captured. As can be seen in Fig. 4, capture in In^{115}, Eu^{151}, Lu^{176}, and Hf^{177} shows this to be the case. Variations in the ratio of ground-state to isomeric-state activities have been shown[19] to occur when the capturing state of the compound nucleus is selected. Such variations imply that the mode of decay of the capturing state is selective and is not of a purely statistical nature.

In view of the uncertainties associated with the application of the model it is probably not reasonable to attempt to classify capture radiation as to multipole order on the basis of total radiation width measurements.[26] Any statement concerning proper statistical factors to be applied depending upon spins of the capturing states should also await further partial width measurements.[27]

ACKNOWLEDGMENTS

The author wishes to acknowledge the many contributions of Dr. V. L. Sailor with whom he has worked during the progress of this research.

[23] B. B. Kinsey and G. A. Bartholomew, Phys. Rev. **83**, 234 (1951).
[24] Gertrude Scharff-Goldhaber, Phys. Rev. **90**, 587 (1953).
[25] C. O. Muehlhause, Phys. Rev. **79**, 277 (1950).
[26] A. Stolovy and J. A. Harvey, Phys. Rev. **99**, 611 (1955).
[27] D. J. Hughes and J. A. Harvey, Nature **173**, 942 (1954).