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Neutron resonance spectroscopy: ^{154,158,160}Gd†

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Neutron time of flight spectroscopy measurements were made for a range of sample thickness on the even separated Gd isotopes $A = 154$, 158, and 160. These include transmission measurements using 200 and 40 m flight paths and self-indication measurements using a 40 m flight path. Resonance parameters were obtained for 48 levels to 1 keV for ^{154}Gd and for 95 and 56 levels to 10 keV for ^{158}Gd and ^{160}Gd. The experimental s-wave strength functions were $10^4 S_0 = (2.0 \pm 0.3)$, (1.5 ± 0.2), and (1.8 ± 0.4), respectively. For ^{160}Gd, the p strength function is $10^4 S_1 \approx 1.7 \pm 0.3$. Essentially complete s-wave populations were obtained for the first 19 levels in ^{154}Gd with $\langle D \rangle = 14.5 \pm 1.5$ eV and $\Delta_{\text{exp}} = 0.22$ (vs $\Delta_{\text{DM}} = 0.28 \pm 0.11$); 47 levels in ^{158}Gd with $\langle D \rangle = 86 \pm 4$ eV and $\Delta_{\text{exp}} = 0.29$ (vs $\Delta_{\text{DM}} = 0.38 \pm 0.11$); and 20 levels in ^{160}Gd with $\langle D \rangle = 202 \pm 20$ and $\Delta_{\text{exp}} = 0.32$ (vs $\Delta_{\text{DM}} = 0.30 \pm 0.11$). Comparison of the observed Γ_n^0 distributions with the Porter-Thomas theory and the observed level spacings with the Wigner theory and other statistical orthogonal ensemble tests gave good results for the energy intervals over which complete s populations were observed. The average radiation widths were $\langle \Gamma_\gamma \rangle = 88$ meV determined from $n = 25$ levels in ^{154}Gd, $\langle \Gamma_\gamma \rangle = 105$ meV ($n = 27$) in ^{158}Gd and $\langle \Gamma_\gamma \rangle = 111$ meV ($n = 4$) in ^{160}Gd.

[NUCLEAR REACTIONS ^{154,158,160}Gd(n, n), (n, γ), $E = 0$–10 keV; measured $\sigma_t(E)$; deduced E_0, Γ_n, Γ_γ, S_0, $\langle D_0 \rangle$, S_1.]

I. INTRODUCTION

This is one of a series[1-9] of papers reporting the results of high resolution time of flight neutron spectroscopy using the Columbia University Nevis synchrocyclotron. This paper presents the results of resonance parameter analysis of transmission and self-indication measurements using isotopically enriched samples of ^{154}Gd, ^{158}Gd, and ^{160}Gd.

These results on the Gd isotopes are interesting for several reasons. The stable Gd isotopes have mass numbers $152 \leq A \leq 160$, which places them in the valley of the split $4s$ giant resonance of the s strength function S_0. The experimental values of S_0 for these isotopes help to better establish the behavior of the splitting of the $4s$ resonance. This is informative in determining the amount of coupling between various parts of the real and imaginary potential required in optical model calculations, and if spin-orbit coupling terms are needed. It is also of interest to look for systematic decreases of S_0 with mass number for each isotope chain of given Z as reported by Tellier and Newstead of Saclay[10] for the tellurium isotopes and noted by others for Sn,[11] Er,[1] and Sm.[2] The observed tendency to see an increasing ratio of p to s levels for higher A isotopes is partly due to the increasing level spacing, but may partially be due to increasing S_1. The comparisons for Gd are confused by the rapid changes in S_0 predicted by optical model calculations near $A \approx 154$.

Observed long and short range order in the level spacings as predicted by Dyson and Mehta for single level populations obeying the statistical orthogonal ensemble (OE) theory were most conclusively demonstrated in our results[1] for ^{166}Er. We have also seen[1,2,4,5] this satisfied particularly for other even A nuclei having $150 \leq A \leq 190$. These results for ^{154}Gd, ^{158}Gd, and ^{160}Gd give further confirmation of the OE theory predictions concerning level spacings. The average spacing $\langle D \rangle$ of s levels can be related to the binding energy of the extra neutron, with $\langle D \rangle$ rapidly increasing as the binding energy decreases. Finally, the average radiation widths, $\langle \Gamma_\gamma \rangle$ for the Gd isotopes are important in a study of the systematics of Γ_γ in the mass region which are useful, along with the individual resonance parameters and strength functions, in the design of nuclear reactors.

There have been a number of recent measurements on the Gd isotopes. Karzhavina, Phong, and Popov[12] (Dubna) have reported resonance parameters for all of the isotopes. Mughabghab and Chrien[13] (BNL) obtained resonance parameters for ^{155}Gd through ^{160}Gd. Friesenhahn *et al.* (at Gulf General Atomic Incorporated, San Diego, California)[14] and Asghar *et al.* (Saclay)[15] performed measurements on the odd isotopes ^{155}Gd and ^{157}Gd. We obtain resonance parameters for 47 levels of ^{154}Gd to 1 keV, for 93 s levels and 2 p levels of ^{158}Gd to 10 keV, and for 45 s and 13 p levels of ^{160}Gd to 10 keV. This is nearly a factor of 4 greater than previously reported for these isotopes.

II. EXPERIMENTAL DETAILS

Details of the synchrocyclotron velocity spectrometer operation and our analysis methods have been given in previous papers.[1,3] The enriched isotope samples were obtained from the isotope division at the Oak Ridge National Laboratory (ORNL) in the form of Gd_2O_3. They were made into either 32×64 mm or 32×127 mm rectangular samples, using (dilute) polystyrene cement as a binder, and wrapped in thin Al foil. Two thicknesses of ^{154}Gd were used having $(1/n) = 344$ and 712 b/atom ^{154}Gd and 0.26, 0.11, 0.047, 0.052, and 0.028 times as much of the $A = 155$, 156, 157, 158, and 160 Gd isotopes, respectively. Three thicknesses of 95.81% ^{158}Gd were used having $(1/n) = 161$, 240, and 482 b/atom ^{158}Gd. Three thicknesses of 97.86% ^{160}Gd were used having $(1/n) = 184$, 260, and 530 b/atom ^{160}Gd. Only trace amounts of other elements were present and could not account for any of the observed resonances.

III. DATA ANALYSIS

Naturally occurring Gd ($Z = 64$) consists of seven isotopes, of the following A (% abundance): $A = 152$ (0.20), 154 (2.15), 155 (14.78), 156 (20.59), 157 (15.71), 158 (24.78), and 160 (21.79). All the even isotopes have $I = 0$ (+), while the $A = 155$ and 157 isotopes both have $I = (\frac{3}{2})$ (−). The binding energies for an extra neutron added to Gd are 6.49, 6.45, 8.54, 6.36, 7.94, 6.03, and 5.63 MeV, respectively, for the above isotopes. Since our measurements included only three of the seven isotopes, we used other recent data to make some of our resonance assignments, especially for ^{154}Gd, where our sample contained ~33% of other Gd isotopes. For ^{154}Gd, we were able to analyze the data up to ≈300 eV relying mainly on the Dubna data[12] for isotopic identification. Above 300 eV, we see a large number of levels. The strongest of these are due to ^{154}Gd, but we are unable to make positive assignments of the weaker levels. The analysis above 300 eV is therefore confined to the relatively strong ^{154}Gd levels. The ^{158}Gd and ^{160}Gd samples were sufficiently pure that it was possible to make isotopic assignments in these two isotopes with high accuracy over our whole energy range to 10 keV.

Our resonance parameters were obtained from the counts vs energy transmission and self-indication data. The information from each sample thickness implies a relationship between the parameters $(g\Gamma_n, \Gamma_\gamma)$ for each resonance. For all s-wave resonances of the even isotopes of Gd, the statistical spin factor $g = 1$. In favorable cases, the common intersection of the curves uniquely determines Γ_n and Γ_γ. For less favorable cases, we assume $\Gamma_\gamma \approx \langle \Gamma_\gamma \rangle$ in order to determine Γ_n. We were able to obtain Γ_γ for a large number of resonances below a few keV. Examples of such analysis are given in previously published papers[1-4] of this series.

The s or p assignment of a level was made by using a number of statistical tests of the orthogonal ensemble theory. These tests include the Dyson-Mehta Δ statistic, the Wigner nearest neighbor distribution, the Dyson F test, the correlation of adjacent levels, and Bohigas and Flores's $\sigma(k)$ test for levels spacings with k intervening levels. In addition, the Porter-Thomas distribution of Γ_n^0 values must be satisfied for the number of levels with small Γ_n^0. Since a brief summary of this technique is nearly impossible, the reader should see Refs. 1 and 16 for a more thorough discussion of methods of separating s from p levels.

IV. RESULTS

The main tables of our resonance parameters, E_0, Γ_n^0, and Γ_γ (where obtained) for ^{154}Gd, ^{158}Gd, and ^{160}Gd are not given here. They are given, in almost our final form in Ref. 17, where "recommended values" only are given. The tables there on pp. 64-2 and 3, 64-8, 9, and 10, and 64-11 and 12 for ^{154}Gd, ^{158}Gd, and ^{160}Gd mainly present our values. In cases where the recommended values combine our results with those of others, (mainly at lower energies) the tabulated results are consistent with ours except as noted below.

(1) The table, p. 64-2, for ^{154}Gd was mislabeled as ^{152}Gd. The listed energies for ^{154}Gd resonances are ours, to within statistical uncertainties except for the first listed level at 9.41 eV where no level was seen in our data. The Γ_γ values are ours except that for the level at 65 eV. For resonances above 110 eV, the listed Γ_n^0 values are the same as ours to within our quoted uncertainties. Below 110 eV there is generally agreement to within our quoted uncertainties except for the levels at 47.1, 49.5, and 105.6 eV where our Γ_n^0 values are (0.40 ± 0.05), (0.22 ± 0.03), and (0.43 ± 0.03) meV. We also have a comment that the level at 684.7 eV is probably a doublet.

(2) The tables for ^{158}Gd on pp. 64-8, 9, and 10 have our values for most resonances. The exceptions are for five Γ_γ values where the quoted values agree within our uncertainties. Ten listed Γ_n^0 values below 2 keV differ from our values within our uncertainties. The cases where this is not true are for the levels at 242.7, 1351.3, and 1740 eV where we have Γ_n^0 values (2.9 ± 0.4), (0.68 ± 0.40), and (0.07 ± 0.03) meV. In addition,

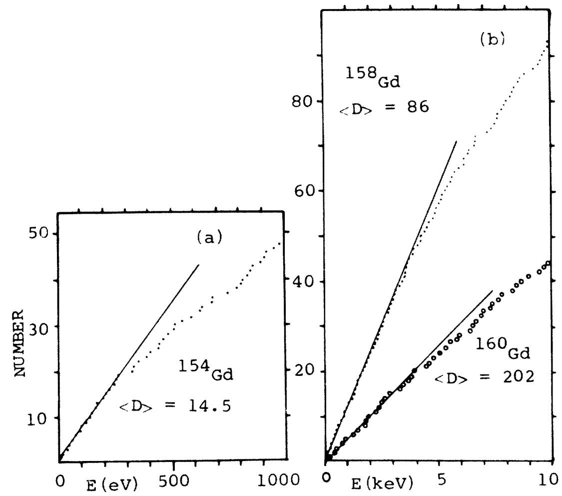

FIG. 1. Plots of observed numbers of s levels in (a) ^{154}Gd and (b) ^{158}Gd and ^{160}Gd vs energy. Two weak levels are not included for ^{158}Gd and 13 ^{160}Gd since they are considered to the $l=1$. The s populations are probably complete for ^{154}Gd to 270 eV, and for ^{158}Gd and ^{160}Gd to 4 keV.

we classify weak levels at 1911 ± 1.0 and 2706 ± 2.0 eV as $l=1$, with $g\Gamma_n^1 = (6.3 \pm 4.0)$ and (6.0 ± 3.5) meV, respectively.

(3) The tabulated parameters for ^{160}Gd on pp. 64-11 and 12 are mainly our preliminary results and agree with our final results except as follows. We did not obtain Γ_γ for the level at 905 eV but the other four Γ_γ values are either the same as ours or agree within our uncertainties. The Γ_n^0 values, there listed $g\Gamma_n^0$, agree to within our uncertainties with our final values except for several levels which we analyze as p levels and list in Table I of this paper, and for four of our levels which are not included. The level at 2396 eV should have $\Gamma_n^0 = (12.3 \pm 1.7)$ meV rather than (112.3 ± 15.3) meV. The four missed weak s levels are at 3343, 4639, 4667, and 4794 eV and have Γ_n^0 values of (0.43 ± 0.20), (1.5 ± 0.7), (1.1 ± 0.6), and (3.5 ± 1.4) meV.

A careful search for the presence of weak levels due to known or suspected impurities in the ^{158}Gd and ^{160}Gd samples indicated that even the strongest levels of the impurity isotopes are not observed. This reassures us that all of the reported levels in ^{158}Gd and ^{160}Gd have the proper isotopic assignment.

Figures 1 (a) and (b) show plots of the cumulative number of levels, N, vs E for ^{154}Gd, ^{158}Gd, and ^{160}Gd. The plot for ^{158}Gd omits the two levels considered to be $l=1$ and that for ^{160}Gd omits the 13 levels of Table I which are considered to be $l=1$. The plot for ^{154}Gd shows a good fit to a straight line for the first 19 levels to 269 eV, above which energy we begin to miss a significant number of weak s levels. This energy also corresponds roughly to the upper energy at which we were able to make positive isotopic identifications for our ^{154}Gd data. Above this energy, some of the missed weak s levels undoubtedly correspond to our observed weaker levels for the ^{154}Gd sample which we were unable to assign definitely to ^{154}Gd.

For ^{158}Gd, few if any s levels were missed to 4 keV, while after excluding the levels in Table I for ^{160}Gd considered to be p levels, we seem to see all of the ^{160}Gd s levels to 4 keV.

Figures 2 (a), (b), and (c) show $\sum \Gamma_n^0$ vs E for these three isotopes. The slopes give the s strength functions, S_0, and are insensitive to missed weak s levels. The slope for ^{158}Gd is smooth, but those for ^{154}Gd and ^{160}Gd vary more between localized regions of sudden increase. Figures 3 (a), (b), and (c) compare the observed histograms for the $(\Gamma_n^0)^{1/2}$ distributions with the single channel Porter-Thomas (PT) forms. The theoretical PT curves are normalized to the measured strength functions and to our best estimates for the correct s level densities. The ^{154}Gd fit implies about 22 missed weak s levels between 270 eV and 1 keV. The ^{158}Gd histogram is shown

TABLE I. Resonances in ^{160}Gd considered to be $l=1$.

E_0 (eV)	ΔE_0	$g\Gamma_n^1$ (meV)	$\Delta g\Gamma_n^1$	E_0 (eV)	ΔE_0	$g\Gamma_n^1$ (meV)	$\Delta g\Gamma_n^1$
421.9	0.5	40.	20.	1874.	1.0	14.	6.
571.8	0.3	103.	40.	2555.	2.0	30.	15.
707.5	1.0	44.	20.	2899.	0.8	39.	20.
1025.	1.0	20.	10.	3174.	3.0	36.	19.
1291.	1.0	26.	15.	3563.	3.0	44.	23.
1632.	1.0	12.	6.	3598.	3.0	51.	28.
1695.	1.0	20.	11.				

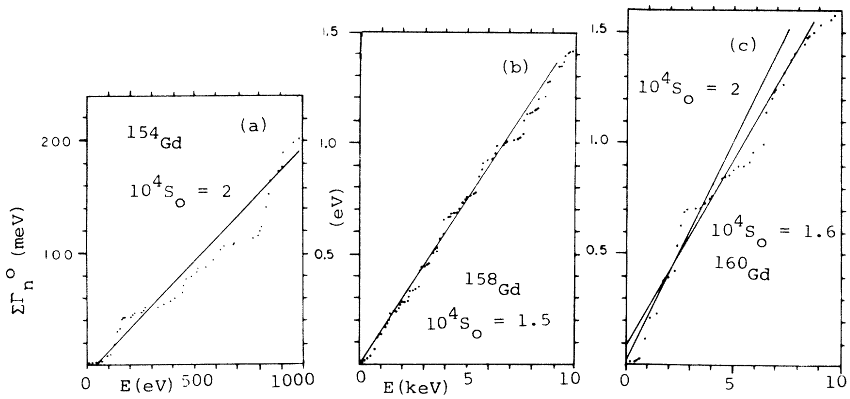

FIG. 2. Plots of $\Sigma\Gamma_n^0$ vs E for (a) ^{154}Gd, (b) ^{158}Gd, and (c) ^{160}Gd. The slopes of these plots give the s strength functions.

with and without the two "p levels" in the first histogram box. The ^{160}Gd plot clearly suggests that about 13 extra weak levels are present to 4 keV. For constant s and p strength functions, S_0 and S_1, and sample thickness $(1/n)$, we are more apt to observe p levels in the available relatively thin $(1/n)$ separated isotope samples when $\langle D\rangle$, and thus $\langle\Gamma_n^0\rangle$ and $\langle\Gamma_n^1\rangle$, are larger. There also seems to be a trend for S_1 to increase with A for a given Z, in many cases.

The mean square deviation of the plot of observed N vs E for a single orthogonal ensemble (OE) population, denoted Δ, constitutes the Dyson-Mehta Δ statistic which was best verified by our results[1] for ^{166}Er. Applied to the 19 levels of ^{154}Gd to 270 eV we have $\Delta_{\text{exp}} = 0.22$ which is in excellent agreement with $\Delta_{\text{DM}} = (0.28 \pm 0.11)$. Figure

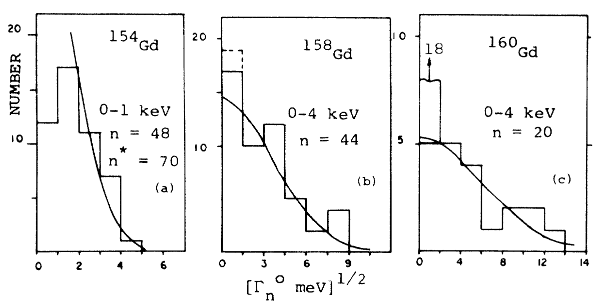

FIG. 3. Comparisons of the histograms of $(\Gamma_n^0)^{1/2}$ with the single channel Porter-Thomas formula, normalized to the observed strength functions and to our final choice $\langle D\rangle$ values. The fits are reasonably good, except for the first histogram boxes where (a) there are missed weak ^{154}Gd s levels above 270 eV. Probably all s levels are seen in (b) ^{158}Gd and (c) ^{160}Gd to 4 keV, but 2 and 13 extra weak p levels are present. The first histogram boxes are shown with and without these weak p levels.

4(a) shows that the nearest neighbor level spacing distribution agrees well with the Wigner formula. The correlation coefficient, ρ, for adjacent nearest neighbor spacings, $-(0.56 \pm 0.23)$ is slightly over 1 standard deviation from the theoretical value $\rho \approx -0.27$.

When the two weak p levels are removed from the ^{158}Gd s population to 4 keV, we obtain $\Delta_{\text{exp}} = 0.29$ and $\rho = -(0.14 \pm 0.15)$ in good agreement with $\Delta_{\text{DM}} = (0.38 \pm 0.11)$ and the theoretical $\rho \approx -0.27$. Tests using the Dyson F statistic, before removing the two weak p levels, showed two fluctuations greater than 2σ at the position of these levels. After removing these levels the fluctuation stayed near one unit of σ from the mean. A good agreement with theory is seen for the resulting nearest neighbor level spacing in Fig. 4(b).

The resulting s level population for ^{160}Gd to 4 keV, after removing the 13 p levels has $\Delta_{\text{exp}} = 0.32$ (vs $\Delta_{\text{DM}} = 0.30 \pm 0.11$), and $\rho = -(0.33 \pm 0.17)$, both in excellent agreement with OE theory. The Dyson F statistic test was also good after removing the 13 levels, but poor when they were present. The nearest neighbor level spacing, Fig. 4(c), is also in satisfactory agreement with the Wigner formula when the p levels are removed.

Figures 5(a) and (b) show the behavior of $\sigma(k)$, the standard deviation in units of the nearest neighbor $\langle D\rangle$ of the spacings of levels having k levels between, vs k. The 10 and 90% confidence limits from OE theory and the favored values are shown for comparison, along with the Uncorrelated Wigner (UW) curve for a set of adjacent spacings drawn randomly from a single Wigner distribution. The agreement with OE theory is also excellent in each case for this test.

The final choices for the population average

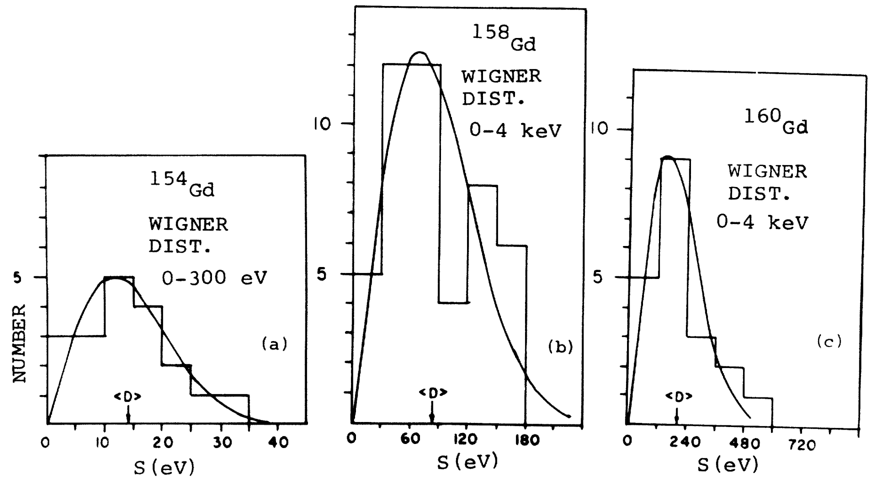

FIG. 4. Comparison of the nearest neighbor s level spacing distributions for (a) ^{154}Gd, (b) ^{158}Gd, and (c) ^{160}Gd with the Wigner formula. The weak p levels are not included for ^{158}Gd and ^{160}Gd.

parameters are listed in Table II. The indicated fractional uncertainties in the S_0 values are $(2/n)^{1/2}$, based only on statistical considerations. The n values including missed weak s levels, i.e., $n = \Delta E/\langle D\rangle$ where $\Delta E = 1$, 10, and 10 keV for ^{154}Gd, ^{158}Gd, and ^{160}Gd, respectively. The evaluation of $\langle D_0\rangle$ is based on our fits by the Dyson-Mehta Δ test to N vs E where no s levels are missed ($n = 19$, 47, and 20, respectively).

Our choice $10^4 S_0 = (2.0 \pm 0.3)$ for ^{154}Gd to 1 keV compares with $(2.1^{+1.5}_{-0.7})$ of Karzhavina *et al.*[12] to 224 eV. We would obtain the same result to this energy [see Fig. 2(a)]. Our choice $10^4 S_0 = (1.5 \pm 0.2)$ for ^{158}Gd to 10 keV compares with $(1.6^{+0.8}_{-0.5})$ of Karzhavina *et al.* to 2338 eV, (1.6 ± 0.6) of Mughabghab and Chrien[13] to 917 eV. Both of these results are consistent with ours for the indicated energy ranges. Our choice $10^4 S_0 = (1.8 \pm 0.4)$ for ^{160}Gd to 10 keV compares with $(2.7^{+1.7}_{-0.9})$ for Karzhavina *et al.* to 2656 eV, and (2.5 ± 1.3) for Mughabghab and Chrien to 2679 eV.

We would obtain 2.2 to 2640 eV, in reasonable agreement with their values. It is seen from Fig. 2(c) that the average slope for $\sum \Gamma_n^0$ decreases at higher energies.

Excess weak levels, considered p levels, were observed in ^{158}Gd and ^{160}Gd. In ^{160}Gd, there were enough p levels to allow us to estimate the p strength function S_1. Eight p levels below 2 keV are seen for this isotope; the measurements above 2 keV have a greatly reduced detection efficiency and have less reliable $g\Gamma_n^1$ values. Assuming that the p level density is $(2l+1) = 3$ times that of s levels, and the same $\langle g\Gamma_n^1\rangle$ for both J states, we can estimate S_1 from the Porter-Thomas theory. We observed six levels with $g\Gamma_n^1 \geq 20$ meV and eight levels with $g\Gamma_n^1 \geq 12$ meV in the energy range 0–2 keV which implies $1.4 \leq 10^4 S_1 \leq 2.0$. We choose $10^4 S_1 = 1.7 \pm 0.3$. This result is greatly dependent on the choice of p levels, missed or spurious levels. S_1 for ^{160}Gd seems to be considerably greater

TABLE II. Population average parameters.

	$S_0\,(\times 10^4)$	$S_1\,(\times 10^4)$	$\langle\Gamma_\gamma\rangle$ (meV)	$\langle D_0\rangle$ (eV)
^{154}Gd	2.0 ± 0.3		$88 (n = 25)$	14.5 ± 1.5
^{158}Gd	1.5 ± 0.2		$105 (n = 27)$	86 ± 4
^{160}Gd	1.8 ± 0.4	1.7 ± 0.3	$111 (n = 4)$	202 ± 20

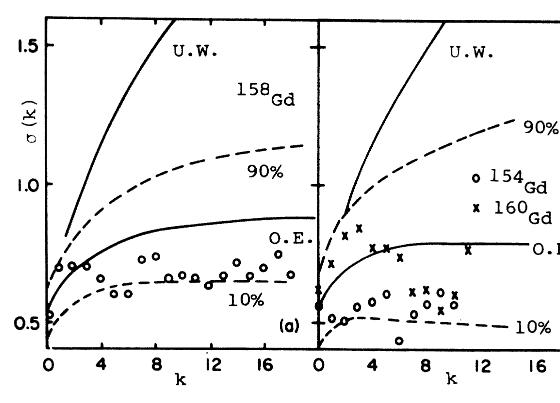

FIG. 5. Comparison of the observed $\sigma(k)$ vs k with the predicted results for the OE and UW theories, with the 10 and 90% limits shown for the OE theory. $\sigma(k)$ is the standard deviation from their mean for the spacings of levels having k ($l = 0$) levels between (in units of $\langle D\rangle$).

than for ^{158}Gd, where only one p level was observed in the first 2 keV, using a somewhat thicker self-indication sample.

We have found the radiation width Γ_γ for 25 levels in ^{154}Gd. They were all close to an average value of ≈88 meV. We estimate a systematic uncertainty of about ±10% in $\langle\Gamma_\gamma\rangle$. A χ^2 analysis yields $\nu \geq 100$ degrees of freedom, much lower than expected from theoretical considerations. The variance is due mainly to experimental uncertainties in the individual Γ_γ values. Karzhavina *et al.*[12] reported $\langle\Gamma_\gamma\rangle = (63 \pm 15)$ meV. For ^{158}Gd, we obtained $\langle\Gamma_\gamma\rangle = 105$ meV with $\nu \approx 70$ degrees of freedom, based on Γ_γ values for 27 resonances. Other values reported in the literature are (89 ± 13) meV by Karzhavina *et al.* and 108 meV (1 resonance) by Mughabghab and Chrien. In ^{160}Gd, we obtain $\langle\Gamma_\gamma\rangle = 111$ meV from four resonances, compared to (98 ± 15) meV by Karzhavina *et al.* Our radiation widths are consistently higher than those of the Dubna group. The reason for this is not clear. We determined many more individual Γ_γ values than they reported (respectively, three, six, and three values). For the resonances for which both we and the Dubna group have determined Γ_γ values, ours are nearly always higher, so that the discrepancy seems to be systematic in nature. Assuming that $\langle\Gamma_\gamma\rangle$ only slowly varies with the mass number A, we can compare with the high precision capture measurements of Ref. 14 (GGA) on the odd Gd isotopes. They find $\langle\Gamma_\gamma\rangle = (107 \pm 3)$ meV for ^{155}Gd and (103 ± 2) meV for ^{157}Gd, which values are in better agreement with our results than with those of the Dubna group.

We find no apparent correlation between the reduced neutron widths Γ_n^0 and radiation widths Γ_γ in ^{154}Gd and ^{158}Gd, where we find the correlation coefficient $\rho(\Gamma_n^0, \Gamma_\gamma) = (-0.17 \pm 0.18)$ and (0.16 ± 0.13), respectively. Both these values of ρ are consistent with zero to within 1 standard deviation.

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[1]H. I. Liou *et al.*, Phys. Rev. C 5, 974 (1972), Er.

[2]F. Rahn *et al.*, Phys. Rev. C 6, 251 (1972), Sm, Eu.

[3]F. Rahn *et al.*, Phys. Rev. C 6, 1854 (1972), ^{232}Th, ^{238}U.

[4]H. I. Liou *et al.*, Phys. Rev. C 7, 823 (1973), Yb.

[5]H. S. Camarda *et al.*, Phys. Rev. C 8, 1813 (1973), W.

[6]F. Rahn *et al.*, Phys. Rev. C 8, 1827 (1973), Na.

[7]U. N. Singh *et al.*, Phys. Rev. C 8, 1833 (1973), K.

[8]H. I. Liou *et al.*, Phys. Rev. C 10, 709 (1974), Cd.

[9]G. Hacken *et al.*, Phys. Rev. C 10, 1910 (1974), In.

[10]H. Tellier and C. M. Newstead, in Proceedings of the Third Conference on Neutron Cross Sections and Technology, Knoxville, Tennessee, 1971.

[11]T. Fuketa, F. A. Khan, and J. A. Harvey, Bull. Am. Phys. Soc. 8, 71 (1963).

[12]E. N. Karzhavina, N. N. Phong, and A. B. Popov, Yad. Fiz. 9, 897 (1969) [transl.: Sov. J. Nucl. Phys. 9, 523 (1970)].

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

[14]H. Friesenhahn, M. P. Fricke, D. G. Costello, W. M. Lopez, and A. D. Carlson, Nucl. Phys. A146, 337 (1970).

[15]M. Asghar, P. Ribon, E. Silver, and J. Trochon, Nucl. Phys. A145, 549 (1970).

[16]H. I. Liou, H. S. Camarda, and F. Rahn, Phys. Rev. C 5, 1002 (1972).

[17]*Neutron Cross Sections*, compiled by S. F. Mughabghab and D. I. Garber, Brookhaven National Laboratory Report No. BNL-325 (National Technical Information Service, Springfield, Virginia, 1973), 3rd ed., Vol. I.