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S-Wave Neutron Strength Functions of the Gd Isotopes*

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The neutron resonance structure of the gadolinium isotopes Gd^{155}, Gd^{156}, Gd^{157}, Gd^{158}, and Gd^{160} has been investigated over a wide energy region to determine the *s*-wave neutron strength functions, resonance parameters, and potential scattering radii. Values of the neutron strength functions as derived from an analysis of the average cross section in the keV region are found to be 2.4±0.2, 1.9±0.4, and 2.2±0.2, all in units of 10^{-4}, for Gd^{155}, Gd^{156}, and Gd^{157}, respectively. For Gd^{158} and Gd^{160}, the values, as obtained from the resonance parameters, are 1.6±0.6 and 2.5±1.3. In addition, the 2200-m/sec cross sections and absorption resonance integrals are computed and are compared with available experimental data.

1. INTRODUCTION

The study of the resonance parameters and *s*-wave neutron strength functions of the gadolinium isotopes is of great interest for searching for any possible spin dependence of the strength function and for the purpose of reactor calculations. The lack of absorption resonance integral measurements of the separated isotopes makes it necessary to compute these quantities from the resonance parameters. In addition, the even-odd isotopes Gd^{155} and Gd^{157} both have target spin $I=\frac{3}{2}$. The relevance of this is due to the fact that considerable data[1] from Saclay indicate that the *s*-wave neutron strength functions for nuclei with target spin of $\frac{3}{2}$ are spin-dependent. There seems to be a systematic tendency for the strength function belonging to resonances with $J=2$ to be larger than those with $J=1$. This method for searching for spin dependence of the strength function suffers from the limited number of identified and studied resonances. Since we made no attempt to measure the spins of individual resonances, we searched for a possible spin dependence of the strength function on target spin I for 16 nuclei ranging from Gd^{155} to Yb^{176} and whose target spins vary from $I=0$ to $I=\frac{7}{2}$. A correlation study between strength function and target spin I revealed no spin dependence between these two quantities in this mass region.[2,3] Detailed results on the Er and Yb isotopes were reported previously.[4,5] In this paper, we present our investigations on the Gd isotopes. Early results on these were reported[6] and preliminary data can be found in Ref. 7.

2. EXPERIMENTAL PROCEDURE

Detailed descriptions of the experiment can be found in Ref. 4. Transmission measurements of Gd samples in powdered oxide form were carried out at the BNL fast-chopper facility of the BGRR reactor. The sample compositions as furnished by the Isotope Division of the Oak Ridge National Laboratory are shown in Table I. The last row of this table gives the sample thicknesses in units of 10^{-3} atoms/b calculated on the basis that the chemical composition of these oxide samples is Gd_2O_3. All measurements were made at the 29.735-m station. No attempt was made to measure the thermal cross sections since very thin and/or highly enriched samples are required because of the large cross sections of Gd^{155} and Gd^{157}. The fast-chopper rotor was spun at speeds of 10 000 and 2000 rpm. A transmission run covering up the energy range from ≈15 keV to 18 eV was carried out for all the isotopes. Since no resonance parameters had been reported[8] for the even-even isotopes, an additional run for these isotopes was made to cover up the energy region down to 1.11 eV. Another run with a delay of 256 and $\frac{1}{2}$-μsec channel width was also carried out for Gd^{157}. In these measurements all 1024 channels in the time analyzer system were utilized to record events with the sample in the beam position. Another separate data run was carried out to record the "open" beam events. The normalization procedure as described in Ref. 4 is accomplished subsequently in a separate run.

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[3] R. E. Chrien, S. F. Mughabghab, M. R. Bhat, and A. P. Jain, Phys. Rev. Letters **24B**, 573 (1967).
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[5] S. F. Mughabghab and R. E. Chrien, Phys. Rev. **174**, 1400 (1968).
[6] S. F. Mughabghab, A. P. Jain, and R. E. Chrien, Bull. Am. Phys. Soc. **9**, 94 (1964).
[7] M. D. Goldberg, S. F. Mughabghab, S. N. Purohit, B. A. Magurno, and V. M. May, Brookhaven National Laboratory Report No. 325 (U.S. Government Printing Office, Washington, D.C., 1958), 2nd ed., Suppl. 2, Vol. IIC.
[8] J. D. Hughes, B. A. Magurno, and M. K. Brussel, in Ref. 7.

TABLE I. Percentage compositions of the Gd samples. Each row gives the percentage abundance of the indicated sample, except that the last row refers to the total sample thickness.

% Isotopic composition	Gd^{155}	Gd^{156}	Gd^{157}	Gd^{158}	Gd^{160}
Gd^{152}	0.05	<0.02	0.01±0.01	<0.1	<0.01
Gd^{154}	0.95±0.05	0.10±0.02	0.07±0.01	<0.1	0.05
Gd^{155}	75.1±0.1	1.18±0.02	1.34±0.05	0.96±0.05	0.52±0.05
Gd^{156}	17.7±0.1	95.25±0.03	7.30±0.05	1.70±0.05	0.82±0.05
Gd^{157}	3.91±0.05	1.72±0.02	69.6±0.1	3.56±0.05	1.19±0.05
Gd^{158}	2.61±0.05	1.26±0.02	19.5±0.1	92.0±0.1	3.42±0.05
Gd^{160}	0.77±0.05	0.49±0.02	2.12±0.05	1.82±0.05	94.0±0.05
n(10^{-3} atom/b)	9.64	11.37	12.77	11.91	10.41

3. DATA ANALYSIS

The resonance parameters are derived by the method of area analysis using a BNL version[9] of the Atta-Harvey code.[10] Where no radiation widths are determined, a value of 110±15 meV is assumed in the analysis. This is based on a weighted average value of radiation widths determined in this experiment. In a few favorable cases, radiation widths are obtained by the thick-thin sample method.[11] Neutron strength functions are extracted by two methods: (a) from reduced neutron widths obtained in the completely and the partially resolved low-energy region and (b) from the average transmission in the 5–15-keV energy interval after applying corrections to the data as previously described.[12]

4. RESULTS AND DISCUSSIONS

A. Resonance Parameters and Average Level Spacings

Figure 1 exhibits the fitted transmission data of Gd^{156} and Gd^{158} isotope samples in the low-energy region. The majority of the resonances that show up here are due to Gd^{155} and Gd^{157} impurities in the sample. The isotopic assignment and energy of each resonance are indicated in the figure. As shown, the over-all fits to the data are very good. The parameters of the low-energy resonances at 2.01, 2.57, and 2.83 eV obtained here are in excellent agreement with the reported BNL crystal spectrometer data.[13] Figure 2 shows a portion of the fitted transmission data of Gd^{156} in the high-energy region. Figures 3 and 4 illustrate the fitted transmission data of Gd^{155} and Gd^{157} in the respective energy regions 49.6–18.0 and 73.2–14.9 eV. In the Gd^{155} transmission data, the resonances at energies of 29.5 and 30.0 eV are not resolved. However, these show up as impurities, for example, in the Gd^{157} transmission data, where they are resolved (Fig. 4). The resonance at about an energy of 22.2 eV which appears in the Gd^{155} transmission run cannot be explained totally in terms of contributions due to the 22.2-eV resonance in Gd^{158}. The dashed curve in Fig. 3 describes the Gd^{158} contribution. Possibly Gd^{155} has a resonance at about this energy with a $2g\Gamma_n \approx 1.2$ meV and/or Gd^{154} has a strong resonance at about this energy. The latter possibility is substantiated by recent Columbia data[14] and earlier Harwell data.[15] Similarly, the resonance at 33.5 eV which shows up in the Gd^{155} transmission data cannot be totally accounted for in terms of contributions due to Gd^{156}. Gd^{155} must then have a resonance at about this energy.

The radiation widths for a few resonances are extracted by the standard technique of plotting the variation of the neutron width derived from assumed values of the radiation width for several sample thicknesses. This is illustrated in Fig. 5 for resonances at 16.7, 22.2, and 33.2 eV belonging to Gd^{157}, Gd^{158}, and Gd^{156}, respectively. The values derived here are in good agreement with those reported by Møller *et al.* for the low-energy resonances and with recent preliminary data of Lopez *et al.*[16] and Morgenstern *et al.*[17] It is interesting to note that the average radiation width of the Gd isotopes is slightly larger than that of nuclei around the same mass region such as Nd and Er.[7] On the other hand, the Dy isotopes exhibit a similar tendency.[18] Such behavior is not predicted by the calculations of Cameron.[19] Later, Cameron[20] proposed a direct-capture

[9] M. R. Bhat and R. E. Chrien, Phys. Rev. **155**, 1362 (1967).
[10] S. E. Atta and J. A. Harvey, Oak Ridge National Laboratory Report No. ORNL 3205, 1961 (unpublished).
[11] D. J. Hughes, J. Nucl. Energy **1**, 237 (1955).
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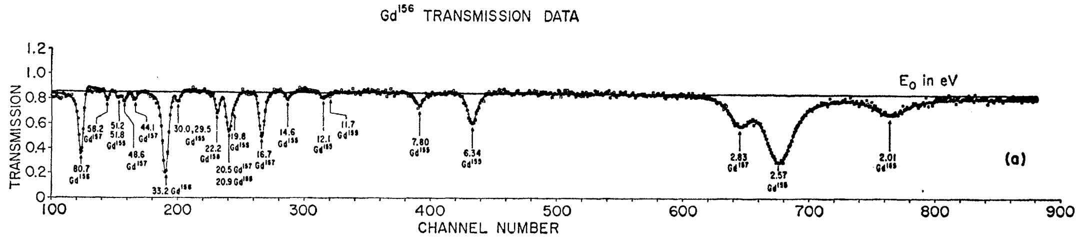
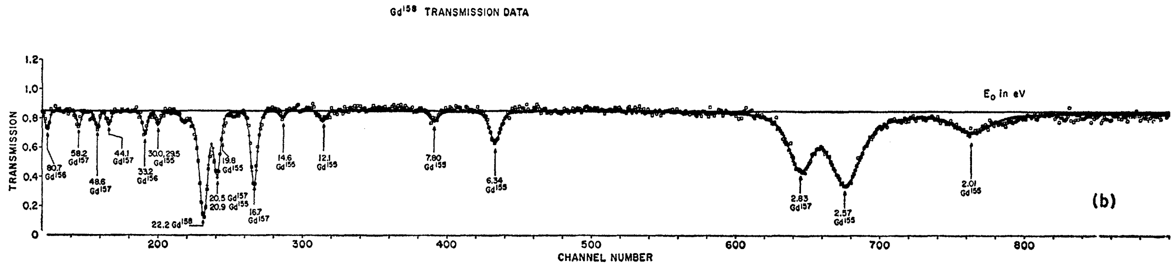
[13] H. B. Møller, F. J. Shore, and V. L. Sailor, Nucl. Sci. Eng. **8**, 183 (1960).
[14] S. Wynchank, M. Slagowitz, J. Rainwater, and W. W. Havens (private communication).
[15] E. M. Bowey and J. R. Bird, Nucl. Phys. **5**, 294 (1957).
[16] W. M. Lopez, D. Costello, and S. J. Friesenhan (private communication).
[17] J. Morgenstern, R. Alves, S. de Barros, J. Julien, and C. Samour, in *Proceedings of the Neutron Cross Section and Technology Conference, 1968* (U.S. Department of Commerce–National Bureau of Standards, Washington, D.C., 1968), p. 867.
[18] S. F. Mughabghab and R. E. Chrien (private communication).
[19] A. G. W. Cameron, Can. J. Phys. **35**, 666 (1957).
[20] A. G. W. Cameron, Can. J. Phys. **37**, 322 (1959).



(a)



(b)

FIG. 1.(a) Portion of the fitted transmission data of Gd^{156} in the low-energy region (1.5–131 eV). The smooth curve is the calculated transmission including Doppler and experimental resolution broadenings; the squares are the experimental points. Below each dip are marked the energy of the resonance and its isotopic assignment. (b) Fitted transmission data of Gd^{158} in the energy interval 1.5–88.9 eV.

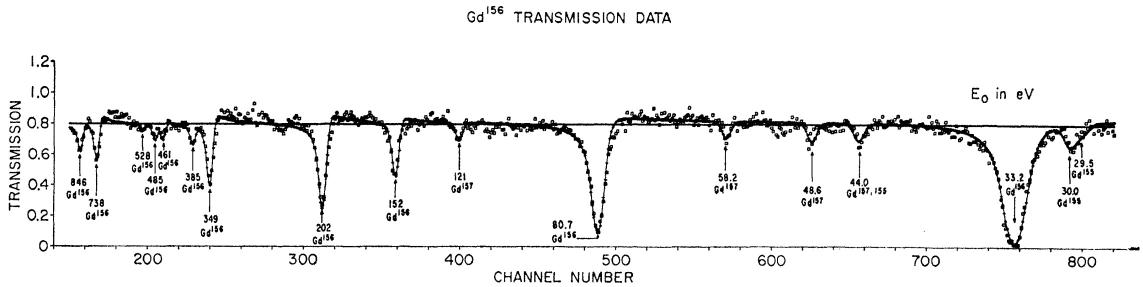


FIG. 2. Example of the fitting procedure for Gd^{156} in a higher-energy region (28–1000 eV). The strong resonances belonging to Gd^{155} and Gd^{157} also have been included in the calculations.

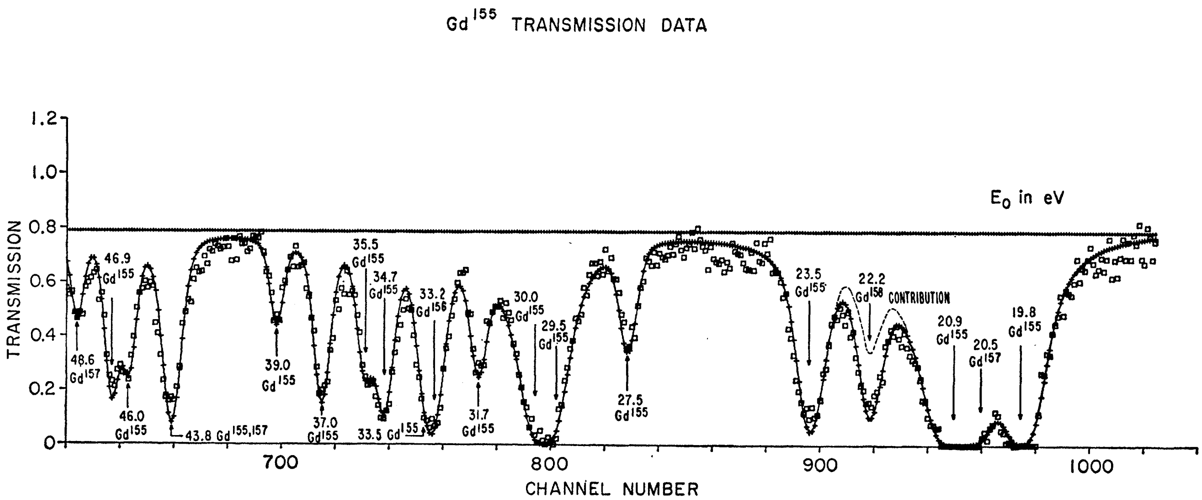


FIG. 3. Fitted transmission data of Gd^{155} in the energy interval 49.6–18.0 eV. The dashed curve around channel 900 is the contribution due to the 22.2-eV resonance of Gd^{158}. Gd^{154} and possibly Gd^{155} also have a resonance about this energy. See text for discussion.

TABLE II. Resonance parameters of the even-odd Gd isotopes Gd^{155} and Gd^{157}. A radiation width of 110 ± 15 meV and a statistical weight factor of $\frac{1}{2}$ are assumed in the analysis. The former number is a weighted average value of radiation widths determined in this experiment.

Gd^{155}

E_0 (eV)	$2g\Gamma_n$ (meV)	Γ_γ (meV)	$2g\Gamma_n^0$ (meV)
0.0268 ± 0.0002[a]	0.130 ± 0.002	108 ± 1	0.800 ± 0.020
2.01 ± 0.02	0.284 ± 0.017		0.200 ± 0.012
2.57 ± 0.02	2.16 ± 0.04		1.35 ± 0.03
6.30 ± 0.09	2.5 ± 0.2		1.00 ± 0.08
7.74 ± 0.12	1.04 ± 0.11		0.37 ± 0.04
10.12 ± 0.12[b]	0.18 ± 0.06		0.058 ± 0.02
11.69 ± 0.22	0.48 ± 0.08[b]		0.14 ± 0.02[b]
12.07 ± 0.23	0.90 ± 0.30		0.26 ± 0.03
14.60 ± 0.31	2.3 ± 0.2		0.6 ± 0.06
19.83 ± 0.08	7.0 ± 0.6		1.57 ± 0.14
20.9 ± 0.09	19.4 ± 1.6		4.24 ± 0.35
~22.2[c]	~1.2		~0.26
23.50 ± 0.11	4.3 ± 0.4		0.89 ± 0.08
27.49 ± 0.13	1.0 ± 0.2		0.19 ± 0.04
29.50 ± 0.15	8.0 ± 3.0		1.5 ± 0.6
30.00 ± 0.15	16 ± 3		2.9 ± 0.6
31.70 ± 0.15	1.7 ± 0.2		0.30 ± 0.04
33.45 ± 0.17	1.3 ± 0.3		0.22 ± 0.05
34.71 ± 0.18	5.8 ± 0.7		0.98 ± 0.12
35.53 ± 0.20	2.5 ± 0.3		0.70 ± 0.05
37.14 ± 0.21	6.8 ± 0.5		1.12 ± 0.08
39.00 ± 0.23	1.2 ± 0.2		0.19 ± 0.03
43.79 ± 0.27	21.9 ± 3.0		3.31 ± 0.45
46.00 ± 0.29	3.9 ± 0.6		0.58 ± 0.09
46.95 ± 0.30	8.3 ± 0.8		1.21 ± 0.12
51.20 ± 0.3	32 ± 5		4.5 ± 0.7
52.1 ± 0.3	26 ± 4		3.6 ± 0.6
53.7 ± 0.3	8.6 ± 2.0		1.2 ± 0.3
56.4 ± 0.4	3.8 ± 0.4		0.51 ± 0.05
59.5 ± 0.4	15 ± 3		1.9 ± 0.4
63.0 ± 0.5	11.6 ± 1.3		1.46 ± 0.16
65.3 ± 0.6	1.2 ± 0.3		0.15 ± 0.04
69.6 ± 0.6	8.6 ± 1.3		1.03 ± 0.16

Gd^{157}

E_0 (eV)	$2g\Gamma_n$ (meV)	Γ_γ (meV)	$2g\Gamma_n^0$ (meV)
0.0314 ± 0.002[a]	0.590 ± 0.010	106 ± 1	3.350 ± 0.050
2.83 ± 0.014	0.435 ± 0.015		0.259 ± 0.009
16.7 ± 0.06	16.1 ± 1.0	130 ± 20	3.94 ± 0.25
20.46 ± 0.09	13.6 ± 0.6		3.00 ± 0.13
21.58 ± 0.09	0.49 ± 0.09		0.11 ± 0.02
23.26 ± 0.10	0.63 ± 0.05		0.13 ± 0.01
25.32 ± 0.12	2.08 ± 0.20		0.41 ± 0.04
40.04 ± 0.24	1.02 ± 0.17		0.16 ± 0.03
44.03 ± 0.27	10.9 ± 2.0	110 ± 20	1.64 ± 0.30
48.64 ± 0.32	29.0 ± 2.0	100 ± 10	4.16 ± 0.29
58.2 ± 0.4	33.6 ± 3.4		4.41 ± 0.44
66.6 ± 0.5	8.8 ± 2.5		1.08 ± 0.31
80.7 ± 0.7	28 ± 6		3.1 ± 0.7
87.4 ± 0.8	6.7 ± 1.0		0.72 ± 0.11
97.0 ± 0.9	21 ± 3		2.1 ± 0.3
100.4 ± 0.9	36 ± 3		3.6 ± 0.3
105.3 ± 1.0	43 ± 8		4.2 ± 0.8
107.6 ± 1.0	9 ± 2		0.87 ± 0.19
110.4 ± 1.1	43 ± 5		4.1 ± 0.5
115.8 ± 1.1	23 ± 2		2.1 ± 0.2
121.2 ± 1.2	140 ± 20		12.7 ± 1.8
138.9 ± 1.5	65 ± 15		5.5 ± 1.3
144.2 ± 1.6	75 ± 15		6.2 ± 1.3
150.2 ± 1.7	23 ± 4		1.9 ± 0.3
157.6 ± 1.8	23 ± 4		1.8 ± 0.3
165.2 ± 2.0	40 ± 20		3.1 ± 1.5
172.0 ± 2.1	70 ± 30		5.3 ± 2.3
178.8 ± 2.2	21 ± 5		1.6 ± 0.4
184.6 ± 2.3	25 ± 5		1.8 ± 0.4

[a] See Ref. 13.
[b] See Ref. 22.
[c] This resonance is in Gd^{154}.

mechanism in which single-particle admixtures in the initial and final states would result in enhanced dipole transitions in the regions near $A=55$ and 160, i.e., where the strength function attains a maximum value. It is interesting to point out[21] that the reduced partial radiation widths reach a maximum near $A=160$.

[21] G. A. Bartholomew, Ann. Rev. Nucl. Sci. 11, 259 (1961).

In Fig. 6, the integrated number of levels are plotted versus incident neutron energy to determine the average level spacings and the energy at which levels are missed significantly. One notices that this takes place in Gd^{155} and, to a lesser extent, in Gd^{157} at about energies of 63 and 184 eV, respectively. For this reason, the resonance parameters of Gd^{155} and Gd^{157} are collected in Table II up to the above-mentioned energies only. For complete-

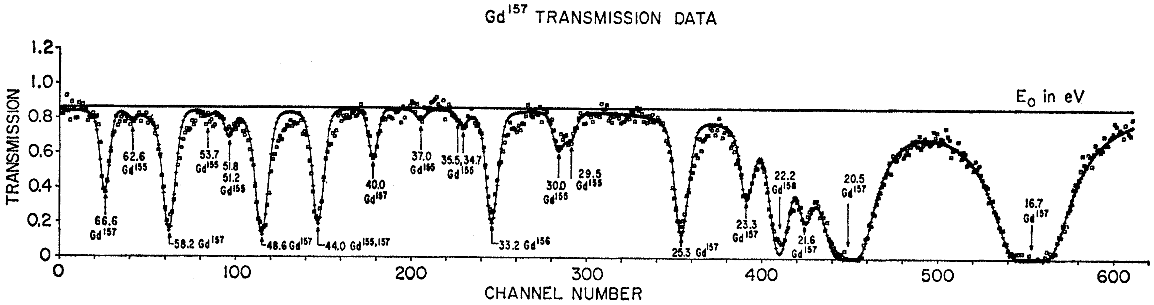


FIG. 4. Fitted transmission data of Gd^{157} spanning the energy region (14.9–73.2 eV). The strong resonances of Gd^{155}, Gd^{156}, and Gd^{158} have also been included in the fitting.

TABLE III. Resonance parameters of the even-even Gd isotopes Gd^{156}, Gd^{158}, and Gd^{160}. A radiation width of 110±15 meV is assumed in the analysis.

E_0 (eV)	Γ_n(meV)	Γ_γ(meV)	Γ_n^0(meV)
	Gd^{156}		
33.2±0.2	14.9±2.0	105±10	2.59±0.35
80.7±0.7	78±12		8.7±1.3
151.9±1.7	45±13		3.7±1.1
202.1±2.6	266±35		18.7±2.5
348±6	450±55		24.1±2.9
385±7	58±15		3.0±0.8
461±9	100±30		4.7±1.4
485±10	100±30		4.5±1.4
528±11	40±20		1.7±0.9
738±18	1280±350		47.1±12.9
846±23	850±200		29.2±6.9
	Gd^{158}		
22.2±0.1	6.8±0.6	108±20	1.44±0.13
242.7±3.5	61±11		3.9±0.7
279±4	8±2		0.48±0.13
346±6	157±22		8.5±1.2
411±8	263±33		13.0±1.6
508±11	252±32		11.2±1.4
587±13	53±13		2.2±0.5
704±17	712±160		26.8±6.0
855±23	1660±240		56.8±8.2
917±26	455±110		15.0±3.6
	Gd^{160}		
223±3	46±8		3.1±0.5
481±10	350±80		15.9±3.6
903±25	3540±580		118±19
1252±40	2780±580		79±16
1440±50	760±360		17±8
1826±70	7040±1130		165±26
2395±100	6650±1660		137±34
2679±120	4660±1170		90±23

ness we have included also the resonance parameters of the levels at 0.0268 and 0.0314 eV obtained by Møller *et al.* and those at 10.12 and 11.69 eV derived by Simpson and Fluharty.[22] The parameters of the even-even Gd isotopes are shown in Table III, while the observed average level spacings are given in the last column of Table IV.

B. Potential Scattering Radius R'

The method of obtaining the potential scattering radius from fitting the transmission data over a large energy region has been described previously.[4] Here we note that water absorption by the Gd oxide samples proved to be the most troublesome among the rare-earth oxides. In a separate experiment water absorption was determined to be 0.46% by sample weight. The values of the potential scattering radius R' are shown in the second column of Table IV.

C. Absorption Resonance Integrals and Thermal Cross Sections

The lack of measurements of absorption resonance integrals of the Gd isotopes motivated us to compute these quantities using the INTTER code[23] and the resonance parameters of Tables II and III along with average resonance parameters from the high-energy

TABLE IV. Summary of potential-scattering radius, neutron strength functions, and average level spacings determined in the present investigation.

Isotope	R'(F)	$10^4\langle g\Gamma_n^0\rangle/D$ (from resonances)	$10^4\langle g\Gamma_n^0\rangle/D$ (from σ_{av})	D(eV)
Gd^{155}	6.7±1.5	2.4±0.3	2.4±0.2	1.9±0.2
Gd^{156}	8.1±0.7	1.8±0.8	1.9±0.4	59±10
Gd^{157}	4.9±1.3	2.4±0.3	2.2±0.2	6.3±0.6
Gd^{158}	6.5±1.0	1.6±0.6	···	92±15
Gd^{160}	6.8±0.8	2.5±1.3	···	300±65

[22] F. B. Simpson and R. G. Fluharty, Bull. Am. Phys. Soc. **2**, 42 (1957).

[23] T. E. Stephenson and S. Pearlstein, Nucl. Sci. Eng. **32**, 377 (1968); and private communication.

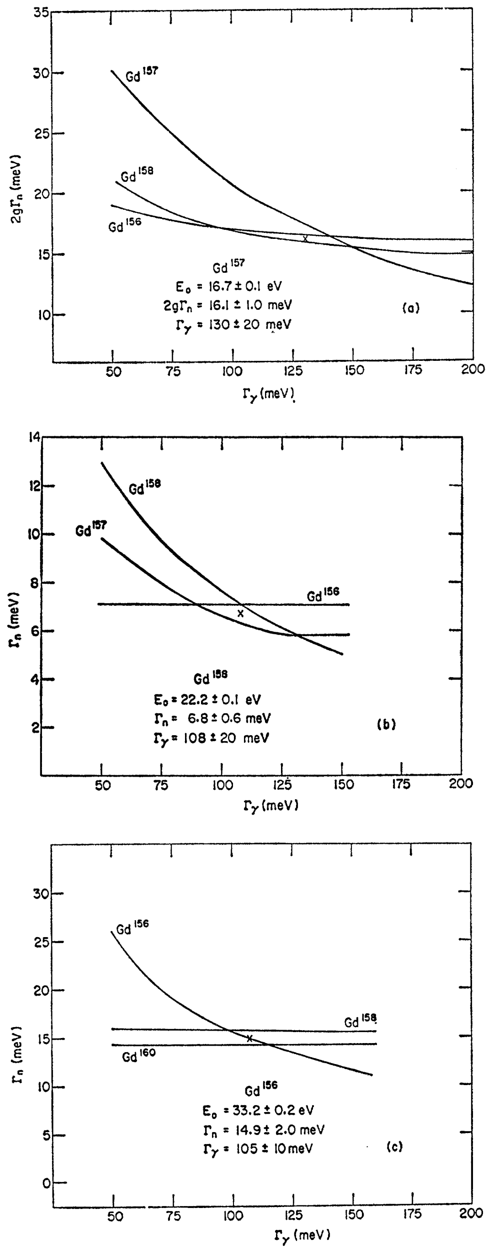


FIG. 5. Radiation widths of the resonances at 16.7, 22.2, and 33.2 eV belonging to Gd^{157}, Gd^{158}, and Gd^{156}, respectively, are determined by the thin-thick sample method. In each case, the curve is labeled by the sample from which the parameters were obtained.

region. The values thus derived are listed in column 3 of Table V, and the energy regions included in the computations for each isotope in column 8.

A search of the literature reveals two previously reported values pertinent to our data; one[24] on Gd^{156} and the other[25] on natural Gd. The former value, 78 ± 21 b, is in satisfactory agreement with a calculated value of 95 b. However, for Gd there is a large discrepancy between the experimental value[25] and the computed one which is obtained by compounding the isotopic absorption resonance integrals by their natural abundances. The contribution from Gd^{154} has been taken into account by adopting the experimental value. In addition, INTTER calculated the 2200 m/sec cross sections, and these are listed in Table V. Again, the agreement between the experimental and the computed values is very good for Gd^{155} and Gd^{157} but not as good for Gd^{156}, Gd^{158}, and Gd^{160}.

The experimental values seem to be high suggesting one of the following possibilities: (1) bound levels which contribute significantly to the thermal cross section, (2) Gd^{155} and Gd^{157} impurities which have not been properly corrected, and (3) a large component of epithermal neutrons in the neutron flux.

Finally, when the isotopic cross sections are compounded by their natural abundance, one obtains $\sigma_a=48\,840$ b for Gd, which is in good agreement with Rustad *et al.*[26] and Cummins and Spurway's[27] values.

D. S-Wave Neutron Strength Functions

Figures 7 and 8 illustrate the method of obtaining the neutron strength functions from the resonance parameters for Gd^{155} and Gd^{157}. The reduced neutron widths of Gd^{155} and Gd^{157} in the energy intervals 70–240 and 185–600 eV are obtained from an analysis of our transmission data in these regions. These reduced widths have not been included in Table III since they represent partially resolved resonances. In addition, the

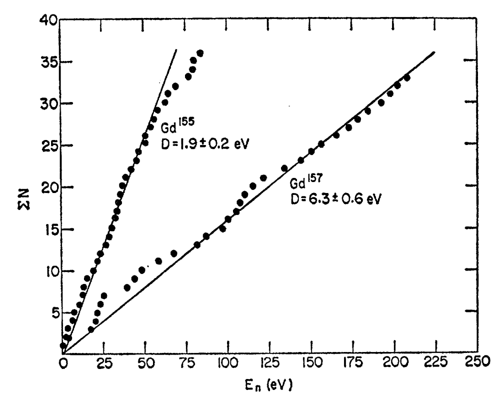


FIG. 6. Cumulative number of resonances are plotted versus neutron energy to determine the average level spacings for Gd^{155} and Gd^{157}.

[24] R. Dobrozemsky, A. Edlmair, F. Pichlmayer, and F. P. Viehlech, private communication to National Neutron Cross Section Center, BNL.

[25] V. B. Klimentor and V. M. Griazev, Atomn. Energ. 3, 507 (1957) [English transl.: J. Nucl. Energy 9, 20 (1959)].

[26] B. M. Rustad, E. Melkonian, W. W. Havens, Jr., T. I. Taylor, F. T. Gould, and J. A. Moore, Rev. Sci. Instr. 36, 887 (1965).

[27] J. D. Cummins and A. H. Spurway, Atomic Energy Research Establishment Report No. AERE R/M 100, 1957 (unpublished).

TABLE V. Calculated thermal absorption cross sections (at 2200 m/sec) and absorption resonance integrals are compared with experimental quantities.

Isotope	% Natural abundance	$I_\gamma(b)$ calc	$I(b)$ Expt	$\sigma_a(b)$ calc	$\sigma_a(b)$ expt	$\sigma_s(b)$ calc	Energy region (eV)
Gd^{154}	2.15		303±31[a]		105±11[a]		
Gd^{155}	14.73	1720.0		60 720.0	60 600±500[b]	71.0	0.0268–240
Gd^{156}	20.47	95.0	78±21[a]	2.0	6.3±1.0[a]	3.9	33.2–846
Gd^{157}	15.68	711.0		254 422.0	254 000±2000[b]	1011.0	0.0314–600
Gd^{158}	24.87	72.0		1.5	3.5±1.0[c]	4.6	22.2–917
Gd^{160}	21.90	4.8		0.18	0.768±0.012[d]	4.1	223–2680
Gd		393.0	67±8[e]	48 840	49 000±2000[c]	172.0	

[a] See Ref. 24.
[b] See Ref. 13.
[c] See Ref. 7.
[d] See S. K. Mangal and P. S. Gill, Nucl. Phys. 41, 372 (1963).
[e] See Ref. 25.

strength functions are derived from an analysis of the average cross section in the keV region. The values obtained by the two methods are given in Table IV, where one notes the good agreement between the two methods. The strength functions are displayed in Fig. 9, where the BNL values[3–5] for the other rare-earth isotopes are also indicated. The optical-model curve is generated by using Buck and Perry's[28] deformation code in which the optical-model parameters of Jain[29] have been adopted on the basis that they give a good fit over all the atomic mass region. The deformation parameters and the energies of the first excited 2^+ states are taken from a compilation by Stelson and Grodzins.[30] One general feature of Fig. 9 is that the experimental values are consistently higher than the predicted curve. This may be an indication[31,32] for a spin-orbit coupling term in the optical potential.

As pointed out before, a correlation study between the strength function and the spin of the target nucleus did not show any dependence between these two quantities. On the other hand, the Saclay data indicate that there is a dependence between the strength function and the spin of the compound states for nuclei with target spins of $\frac{3}{2}$. In addition, recent preliminary data from Saclay[33] on $Gd^{155,157}$ (both with $I=\frac{3}{2}$) did not exhibit any spin dependence of the strength function,

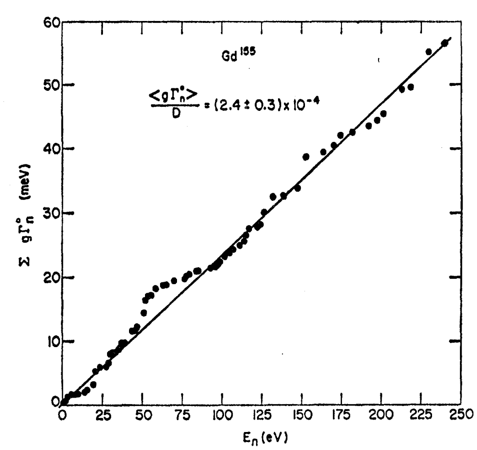


FIG. 7. Cumulative reduced neutron widths for Gd^{155} are plotted against incident neutron energy to find the neutron strength function. The value determined from the resonances is $(2.4\pm 0.3)\times 10^{-4}$, which is in very good agreement with that obtained from the average cross section (see Table IV).

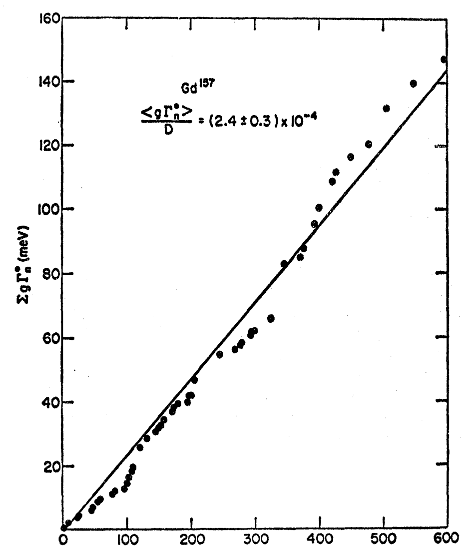


FIG. 8. Neutron strength function of Gd^{157} obtained from resonances is found to be $(2.4\pm 0.3)\times 10^{-4}$. This value is in good agreement with that derived by the average cross-section technique (see Table IV).

[28] B. Buck and F. Perey, Phys. Rev. Letters **8**, 444 (1962); and private communication.
[29] A. P. Jain, Nucl. Phys. **50**, 157 (1964).
[30] P. H. Stelson and L. Grodzins, in *Nuclear Data Sheets*, compiled by K. Way *et al.* (Academic Press Inc., New York, 1965), Vol. 1, No. 1, p. 21.
[31] Yu. P. Elagin, V. A. Lyul'ka, and P. E. Nemirovshii, Zh. Eksperim. i Teor. Fiz. **41**, 969 (1961) [English transl.: Soviet Phys.—JETP **14**, 682 (1962)].
[32] J. E. Lynn, *The Theory of Neutron Resonance Reactions* (Clarendon Press, Oxford, 1968), p. 266.
[33] J. Julien *et al.*, European-American Nuclear Data Committee No. EANDC 89 U, p. 171, 1968 (unpublished).

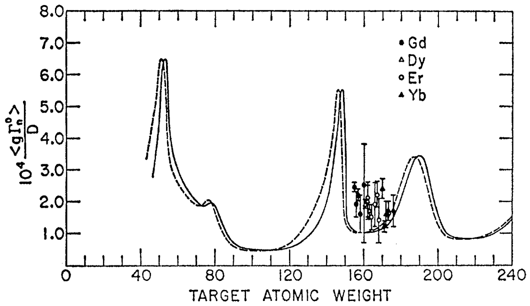


FIG. 9. The s-wave strength functions as obtained by the Buck-Perey optical-model code using the parameters recommended by Jain. The effect of a change of 1 MeV in the real part of the optical-model potential is shown by the dashed curve. It can be seen that in the region of the rare earth the s-wave strength function is insensitive to such a change. In the figure, we have plotted our present results as well as previous results on Er, Yb, and Dy isotopes. For a more complete summary of measured strength functions, see K. K. Seth, *Nuclear Data* (Academic Press Inc., New York, 1966), Vol. 2, Sec. A.

thus corroborating our conclusions in this mass region. Another nucleus with $I=\frac{3}{2}$ in this mass region is Tb^{159}, for which spins assignments of 14 resonances are made.[34,35] Again, no spin dependence is evident in this nucleus. In order to search for a possible explanation of these facts, we have followed a suggestion by Feshbach[36] in which he proposed that the optical potential may have an additional term of the form $\mathbf{I}\cdot\boldsymbol{\sigma}f(r)$, describing a coupling between the spin $\boldsymbol{\sigma}$ of the incoming neutron and the spin of the target nucleus. In terms of the resonance spin J this can be written in the form

$$V(\text{spin-spin})=[J(J+1)-I(I+1)-\sigma(\sigma+1)]\times\tfrac{1}{2}f(r).$$

For s-wave neutrons and nuclei with nonzero target spin, $J=I\pm\frac{1}{2}$. Thus,

$$V_1=I\times\tfrac{1}{2}f(r) \quad \text{for} \quad J=I+\tfrac{1}{2},$$

$$V_2=-(I+1)\times\tfrac{1}{2}f(r) \quad \text{for} \quad J=I-\tfrac{1}{2}.$$

Then the real part of the optical potential for neutrons with spin $I+\frac{1}{2}$ will be different from that for neutrons with spin $I-\frac{1}{2}$ by an amount which is equal to $(2I+1)\times\frac{1}{2}f(r)$. The effect of this on the shape of the neutron strength functions is illustrated by the dashed curve in Fig. 9 for a difference of 1 MeV in the real part of the optical potential. The effective result (considering that I is constant) is to displace the peaks of the dashed curve relative to the solid curve. Such a model would explain why one would not observe any difference in the spin dependence of the strength function in the mass region around $A=160$. On the other hand, one would expect to find a difference around the peaks with $A=53$, 145, and 188. Another aspect of this is that the spin dependence will behave in opposite directions on either side of the peak. Unfortunately, no spin dependence has been conclusively found around $A=53$ so far. One notes also that existing experimental data from Saclay show that the spin dependence manifests itself for nuclei in the mass region $A=63$–81, i.e., mainly for nuclei with $I=\frac{3}{2}$. In this connection, we would like to point out that recent Dubna[37] measurements on Se^{77} ($I=\frac{1}{2}$) showed no spin dependence of the strength function for this nucleus, in disagreement with Saclay's results. Furthermore, Coceva *et al.*[38] have made spin assignments for a total of 46 resonances in Hf^{177} and have shown that the strength function values for each spin state depend sensitively on the spin assignment of a single resonance with a large reduced neutron width. This strongly suggests the need for accurate measurements of spin values before any definite conclusion can be reached about this subject.

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