# Study of Radiation Widths and Neutron Strength Functions of Dy Isotopes*

S. F. Mughabghab and R. E. Chrien
Brookhaven National Laboratory, Upton, New York 11973
(Received 17 November 1969)

Neutron transmission measurements have been carried out for $Dy^{161}$, $Dy^{162}$, $Dy^{163}$, and $Dy^{164}$, employing the fast-chopper facility of the Brookhaven Graphite Research Reactor. The $s$-wave neutron strength functions ($S^0$), resonance parameters, average level spacings, and potential-scattering radii have been determined. The values of the neutron strength functions of $Dy^{161}$, $Dy^{162}$, $Dy^{163}$, and $Dy^{164}$ are $1.85 \pm 0.15$, $2.3 \pm 0.5$, $1.7 \pm 0.2$, and $1.2 \pm 0.5$, all in units of $10^{-4}$. The corresponding average total radiation widths of Dy isotopes are found to be $114 \pm 10$, $155 \pm 15$, $109 \pm 8$, and $55 \pm 3$ meV. A correlation between total radiation width and $S^0$ seems to be evident. Furthermore, examination of the present and previous results for the rare-earth isotopes indicates that there is a systematic trend of decrease of $S^0$ with increasing mass number for the even-even target nuclei. Absorption-resonance integrals and thermal cross sections are computed from the resonance parameters and are compared with direct measurements of other experiments.

## I. INTRODUCTION

This is the conclusion of a series of experiments dealing with the total cross-section measurements of the rare-earth isotopes of Er, Yb, Gd, and Dy. The purpose of these investigations is the study of the systematic properties of neutron resonances in these nuclei. A brief summary of the results can be found in the work of Chrien and Mughabghab.[1] We noted in the study of the Gd isotopes[2] that the average radiation widths of Gd isotopes are slightly higher than those of nuclei around the same mass number such as Nd and Er. Early measurements[3] on samples enriched in the Dy isotopes and carried out at the BNL fast-chopper facility of the Brookhaven Graphite Research Reactor (BGRR) indicated that resonances of the Dy isotopes have the same characteristics. In particular, the resonance at 5.4 eV belonging to $Dy^{162}$ has an unusually large radiation width, $\Gamma_\gamma$, when compared with the other Dy isotopes. By 1957, sufficient measurements of radiation widths were made to warrant a theoretical calculation.[4] Adopting the level-spacing formula developed by Newton,[5] Cameron[4] computed the total radiation widths of resonances. His relationship reproduced qualitatively the general features of the experimental results, such as the general decrease of $\Gamma_\gamma$ with increasing mass number $A$, and the maxima at $A = 138$ and 208. However, it failed to predict the small peak at $A = 162$. Two years later, Cameron[6] suggested that the presence of the peak at $A = 162$ could be related to the $s$-wave neutron strength function.

Subsequently, Sher *et al.*,[7] applied the transmission and activation techniques, using the BNL crystal spectrometer, to determine the total and capture cross sections of $Dy^{164}$ in the thermal-energy region. From their data, they deduced the parameters of a bound level in this isotope. Danelyan *et al.*,[8] measured the capture cross sections of separated Dy isotopes and determined the parameters of bound levels for $Dy^{161}$ and $Dy^{163}$. Using both methods of area and shape analysis, Brunner and Widder[9] obtained the radiation and neutron widths of the resonance at 1.7 eV in $Dy^{163}$.

In 1968, Lynn[10] proposed the valency-nucleon model to indicate that the peak in the region around $A = 165$ can be accounted for in terms of this model. In view of the above considerations and because of the limited amount of data on the Dy isotopes, it is of interest to study and reexamine the radiation widths and the neutron strength functions of the Dy isotopes. Our early results were reported in the compilation of neutron cross sections by Goldberg *et al.*[11]

## II. EXPERIMENTAL PROCEDURE

Transmission measurements of oxide samples enriched in the isotopes $Dy^{161}$, $Dy^{162}$, $Dy^{163}$, and $Dy^{164}$ were carried out at the fast-chopper facility of the BGRR. (The measurements on $Dy^{163}$ were the last to be performed before the fast-chopper facility at the BGRR was phased out in order to give way to the one at the high flux beam reactor which is designed for measurements of $\gamma$ spectra from captured neutrons.) The isotopic analysis of the samples as supplied by the Stable Isotope Division of Oak Ridge National Laboratory is shown in Table I. Each column refers to a particular sample and gives the percentage composition of the isotopes in it. The last row lists the sample thicknesses, $n$, in units of $10^{-3}$ atoms/b, calculated on the basis that the samples are in the sesquioxide

TABLE I. Percentage composition of Dy isotopes used in the present investigation. The last row gives the total sample thickness.

| Isotopic composition | Samples $Dy^{161}$ | $Dy^{162}$ | $Dy^{163}$ | $Dy^{164}$ |
|---|---|---|---|---|
| $Dy^{156}$ | <0.1 | <0.01 | <0.2 | <0.02 |
| $Dy^{158}$ | <0.1 | <0.01 | <0.2 | <0.02 |
| $Dy^{160}$ | 0.59 ± 0.05 | 0.15 ± 0.02 | <0.2 | <0.02 |
| $Dy^{161}$ | 90.0 ± 0.1 | 5.13 ± 0.05 | 2.17 ± 0.05 | 0.40 ± 0.05 |
| $Dy^{162}$ | 7.75 ± 0.10 | 91.04 ± 0.02 | 15.0 ± 0.1 | 1.34 ± 0.05 |
| $Dy^{163}$ | 1.10 ± 0.05 | 2.82 ± 0.05 | 73.3 ± 0.1 | 5.55 ± 0.05 |
| $Dy^{164}$ | 0.56 ± 0.05 | 0.86 ± 0.05 | 9.5 ± 0.1 | 92.71 ± 0.05 |
| $n(10^{-3}$ atoms/b) | 10.87 | 2.80 | 0.75 | 12.28 |

form, $Dy_2O_3$. All measurements were performed at the 29.74-m station. The chopper was spun at speeds of 2000, 6000, and 10 000 rpm. Several data runs were made, covering a large energy region from a few thousand eV to 1.1 eV. For each isotope a data run, spanning the energy interval from about 15 keV to 18 eV, was made. Additional low-energy runs extending the energy interval down to 1.1 eV were carried out for $Dy^{162}$ and $Dy^{164}$. In addition, a $Dy^{163}$ sample with thickness $n = 12.20 \times 10^{-3}$ atoms/b was used for supplementary measurements covering the neutron energy regions of $\simeq 15$ keV–78 eV and 78–8 eV.

## III. DATA ANALYSIS

The background rate for each data run is obtained by two methods: (1) from the "blacked out" resonances, and (2) from the total background rate recorded by the bank of $BF_3$ detectors when a 3-in.-thick Lucite block is placed in the beam. As in the case of the Gd isotopes, the normalization procedure for the transmission data is carried out subsequently in separate runs.[2] The neutron widths are extracted from the transmission data with the aid of a BNL[12] version of the Atta-Harvey[13] code of area analysis. The parameters which are obtained from the area analysis program are then fed into another code which calculates the transmission curve after applying Doppler broadening and instrumental resolution. Examples of computer-produced plots comparing calculated and experimental transmission data are shown in Figs. 1, 2, and 3. In certain favorable cases, it was possible to apply the thin-thick sample method,[14] using the area analysis code, to determine the radiation widths of neutron resonances. The radiation width of the 5.4-eV resonance of $Dy^{162}$ was derived by a combination of area and shape analysis, performed in the following manner. The various neutron widths, $\Gamma_n$, are generated for different assumed values of the radiation widths, $\Gamma_\gamma$. A pair of values, $\Gamma_\gamma$ and $\Gamma_n$, (and hence $\Gamma = \Gamma_n + \Gamma_\gamma$) are then fed into the plot code which calculates the $\chi^2$ value for each resonance. The minimum in $\chi^2$ values is then found, which yields the best fit to the data. An illustration of this is shown in Fig. 1. For resonances where no radiation widths are extracted, a weighted average value of $\Gamma_\gamma$ is assumed in the analysis. For the odd isotopes, $Dy^{161}$ and $Dy^{163}$, a statistical weight factor $g$ equal to $\frac{1}{2}$ is assumed in the analysis and a value of 1 is used for the even isotopes, $Dy^{162}$ and $Dy^{164}$.

The $s$-wave neutron strength functions are obtained from two energy regions: (1) the low-energy region, where individual resonances are completely or partially resolved, using the relationship

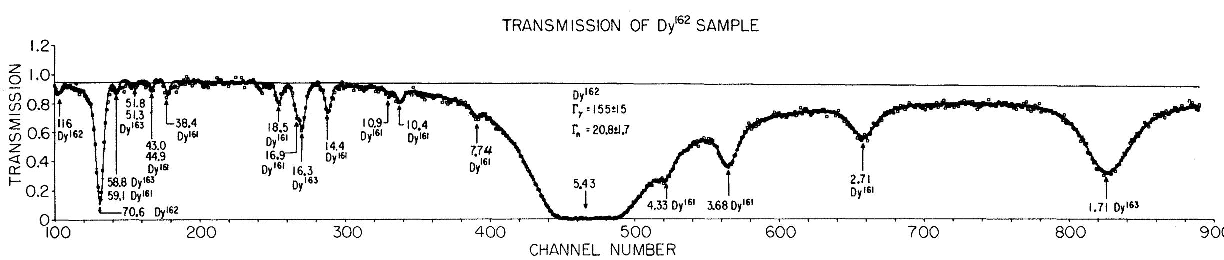


FIG. 1. Illustrates the fitted and experimental transmission data of $Dy^{162}$ sample in the low-energy region. The isotopic assignment and energies of resonances due to other isotopic impurities are also indicated. The baseline is the transmission due to all nonresonant cross-section contributions such as potential scattering.

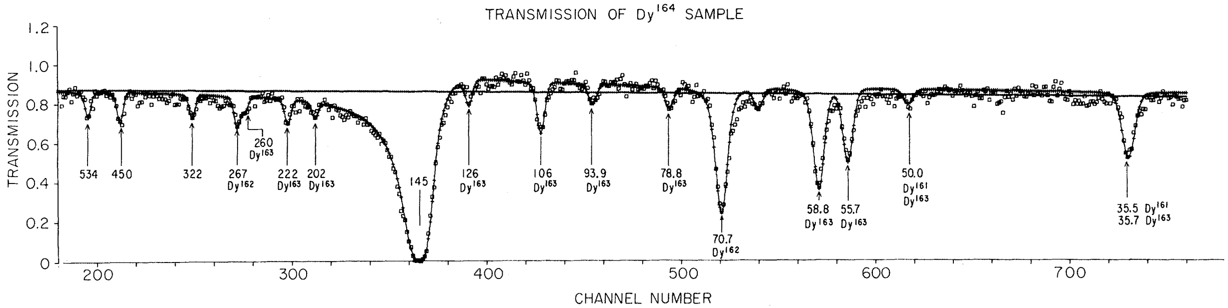


FIG. 2. Fitted transmission data of Dy$^{164}$ sample in energy region 33–635 eV. Below each dip we indicated the resonance energy in eV and the isotope in which it occurs (except for Dy$^{164}$ resonances).

$$S^0=\sum_1^N g\Gamma_n^0/\Delta E$$

(the summation is carried out over $N$ resonances located in an energy interval $\Delta E$), and (2) in the 15–5-keV region, using the average total cross section, $\sigma_{av}$. The latter is described in detail in the work of Chrien.[15]

## IV. DISCUSSION OF RESULTS

### A. Resonance Parameters

The neutron widths, obtained by area analysis, are fed into a code which calculates the transmission curve after applying proper corrections. The resonance parameters are deemed acceptable only

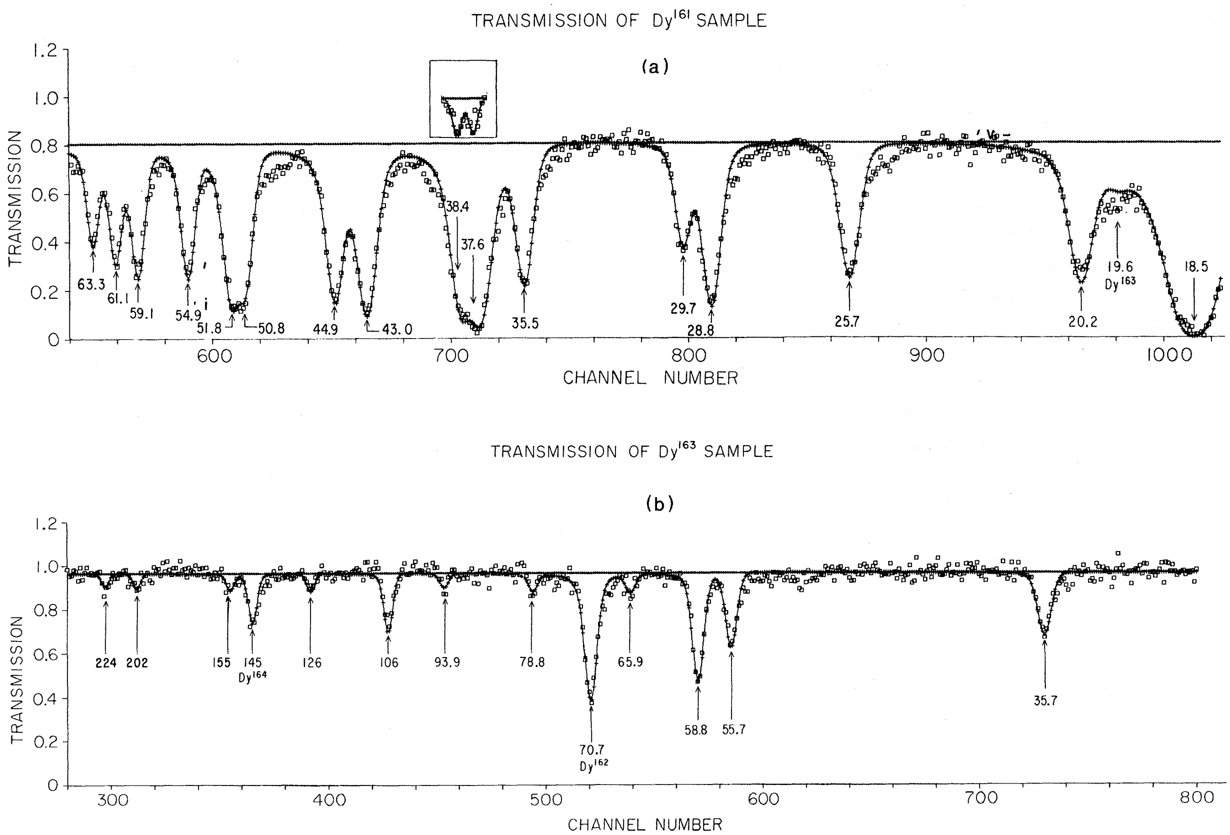


FIG. 3. Fitted transmission data of Dy$^{161}$ and Dy$^{163}$ samples. In the inset of (a) is shown the resolved resonances at energies of 38.4 and 37.6 eV as obtained from transmission of Dy$^{162}$ sample. In (b), all resonances belong to Dy$^{163}$ except those at energies of 70.7 eV (Dy$^{162}$) and 145 eV (Dy$^{164}$). The reason for the noticeably less satisfactory fit in (a) is not known, but may be due to impurity resonances in the sample.

if the resulting fit is satisfactory over a large energy interval. An illustration of such fitting procedure is shown in Fig. 1 for the $Dy^{162}$ sample in the energy interval 120–1.4 eV. A similar good fit, which is not shown here, is obtained for the same sample in a higher energy region from 35 to 1250 eV. Since the $Dy^{162}$ sample is not 100% isotopically enriched, dips corresponding to resonances in various isotopic impurities would show up. The isotopic assignments and the energies of resonances (in eV) are indicated in Fig. 1. The radiation width of the 5.43-eV resonance of $Dy^{162}$ as determined by a combination of area analysis and shape analysis is found to be 155 ± 15 meV. This is in reasonable agreement with Zimmermann's value[3] of 175 ± 45 meV. Analysis of the radiation width of the 70.7-eV resonance of $Dy^{162}$ [as illustrated in Fig. 4(b)] shows that the capture width of this resonance is 150 ± 70 meV. A value of $\Gamma_\gamma = 155 \pm 15$ meV is assumed in the analysis to determine the scattering widths of other resonances in $Dy^{162}$.

An illustration of the fitting procedure for $Dy^{164}$ in a higher-energy region (35–640 eV) is shown in Fig. 2. Area analysis of the 145-eV resonance using two sample thickness ($Dy^{164}$ sample and $Dy^{163}$ thin sample) indicates that a radiation width of 60 meV is favored for this resonance. This is in agreement with Sher *et al.*'s[7] data on the radiation width of the bound level at -1.89 eV. (See Sec. IV.D.) In Table II, a summary of the resonance parameters of the even-even target nuclei, $Dy^{162}$ and $Dy^{164}$, is given. Figures 3(a) and 3(b) represent the transmission data of the $Dy^{161}$ sample and the $Dy^{163}$ sample in the energy intervals indicated. In Fig. 3(a), the pair of doublets at 37.6 and 38.4 eV and at 50.8 and 51.8 eV are not well resolved. However, in the corresponding $Dy^{162}$ sample run (which can be considered as a thin-sample run for $Dy^{161}$), these resonances are fairly well resolved. This is shown in the inset for the pair of resonances at 37.6 and 38.4 eV.

The strong impurity resonances at 70.7 and 145 eV due to $Dy^{162}$ and $Dy^{164}$, respectively, show up here. All other resonances belong to $Dy^{163}$. An illustration of obtaining the radiation widths of resonances of $Dy^{161}$ and $Dy^{163}$ from several sample thicknesses is shown in Figs. 4(a)–(c). The resonance parameters of $Dy^{161}$ and $Dy^{163}$ are summarized in Table III. For completeness, we have

TABLE II. Neutron-resonance parameters of the even-even Dy isotopes, $Dy^{162}$ and $Dy^{164}$. Radiation widths of 150 ±15 and 55 ±3 meV are assumed in the analysis for $Dy^{162}$ and $Dy^{164}$, respectively, for resonances where no $\Gamma_\gamma$ is determined.

| $E_0$ (eV) | $\Gamma_n$ (meV) | $\Gamma_\gamma$ (meV) | $\Gamma_n^0$ (meV) |
|---|---|---|---|
| | $Dy^{162}$ | | |
| 5.43 ± 0.06 | 20.8 ± 1.7 | 155 ± 15 | 9.10 ± 0.72 |
| 70.7 ± 0.5 | 396 ± 20 | 150 ± 70 | 47.1 ± 2.4 |
| 116.4 ± 1.2 | 6.9 ± 1.1 | | 0.64 ± 0.10 |
| 206.1 ± 2.7 | 23 ± 4 | | 1.6 ± 0.3 |
| 222.9 ± 3.0 | 25.5 ± 4.0 | | 1.7 ± 0.3 |
| 267 ± 5 | 580 ± 70 | | 35.5 ± 4.3 |
| 354 ± 6 | 24.5 ± 6.1 | | 1.3 ± 0.3 |
| 409 ± 7 | 85 ± 15 | | 4.2 ± 0.8 |
| 526 ± 11 | 92 ± 23 | | 4.0 ± 1.0 |
| 625 ± 14 | 1410 ± 280 | | 56.3 ± 11.3 |
| 683 ± 17 | 420 ± 160 | | 17 ± 6 |
| 711 ± 17 | 266 ± 100 | | 10 ± 4 |
| 764 ± 19 | 850 ± 260 | | 30.8 ± 6.2 |
| 861 ± 23 | 2550 ± 500 | | 86.9 ± 17.0 |
| | $Dy^{164}$ | | |
| −1.89 ± 0.04[a] | | 55 ± 3 | 41 ± 1 |
| 145.4 ± 1.5 | 868 ± 40 | (60) | 72.0 ± 3.3 |
| 450 ± 9 | 45 ± 11 | | 2.1 ± 0.5 |
| 534 ± 11 | 51 ± 12 | | 2.2 ± 0.5 |
| 855 ± 23 | 500 ± 180 | | 17 ± 7 |
| 1053 ± 31 | 31 ± 11 | | 1.0 ± 0.4 |
| 1190 ± 38 | 480 ± 160 | | 14 ± 4 |
| 1316 ± 44 | 820 ± 330 | | 23 ± 9 |

[a]See also Ref. 7.

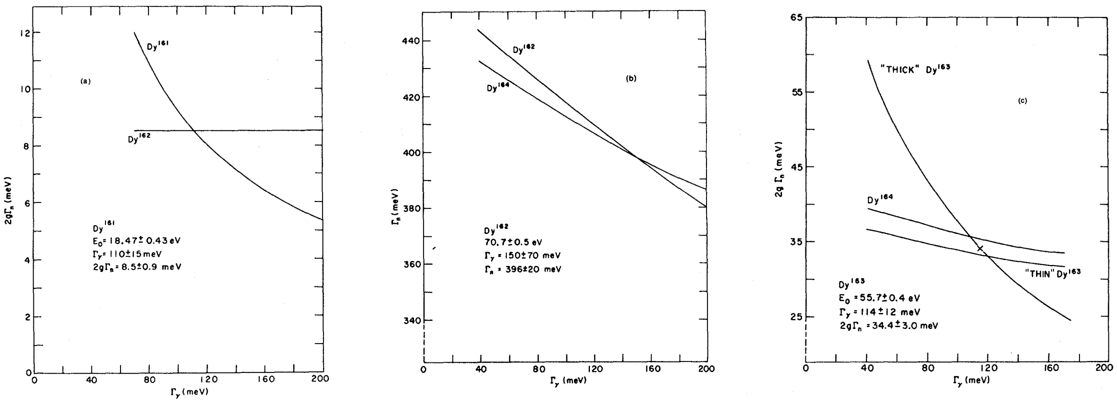


FIG. 4. Radiation widths of the 18.47-, 70.7-, and 55.7-eV resonances in $Dy^{161}$, $Dy^{162}$, and $Dy^{163}$ in (a), (b), and (c), respectively, are derived by the thin-thick sample technique. The samples from which the $2g\Gamma_n$ versus $\Gamma_\gamma$ curves are obtained are shown near each curve.

included in the table the radiation widths of the resonances at 1.71 and 2.72 eV as determined by Zimmerman.[3]

### B. Level Spacings

The total number of resonances below neutron energy, $E_n$, is plotted against $E_n$ for $Dy^{161}$ and $Dy^{163}$ in Fig. 5(a) and for $Dy^{162}$ and $Dy^{164}$ in Fig. 5(b). The observed level spacings $D$ for these isotopes are found to be $2.9 \pm 0.3$, $9.6 \pm 1.1$, $72 \pm 10$, and $200 \pm 38$ eV, respectively. The error in $D$ is computed from $[(4-\pi)/\pi N]^{1/2}$ which is derived from the Wigner distribution of level spacing, and where $N$ is the number of levels. (See, for example, Ref. 10, p.180.) The above error expression is an underestimate for the odd isotopes where two level sequences are randomly superposed. Resonances are missed in $Dy^{161}$ and $Dy^{163}$ at energies of about 100 and 170 eV, respectively. It is estimated that at least 5 resonances are missed in $Dy^{161}$ below an energy of 140 eV and 6 resonances in $Dy^{163}$ below an energy of 280 eV. All the level spacings of the rare-earth isotopes which have been measured by the present authors are compiled in column five of Table IV.

*Note added in proof*: Very recent $(n,\gamma)$ measurement (S. F. Mughabghab, R. E. Chrien, and O. A. Wasson, Bull. Am. Phys. Soc. 15, 4, 1970) on an enriched sample of $Dy^{163}$ shows that there are additional resonances in $Dy^{163}$ at neutron energies of 71.3, 75.2, 85.3, 145, 135, and 187 eV. Some of these resonances in the $\sigma_T$ measurements were "hidden" by the strong impurity resonances at 70.7 and 145.4 eV due to $Dy^{162}$ and $Dy^{164}$, respectively.

### C. Potential Scattering Radius $R'$

The determination of the potential scattering radius $R'$ depends on the accurate measurement of the total cross section between resonances, where the transmission is close to unity. Correction for the influence of scattering amplitudes from nearby resonances must be applied over a

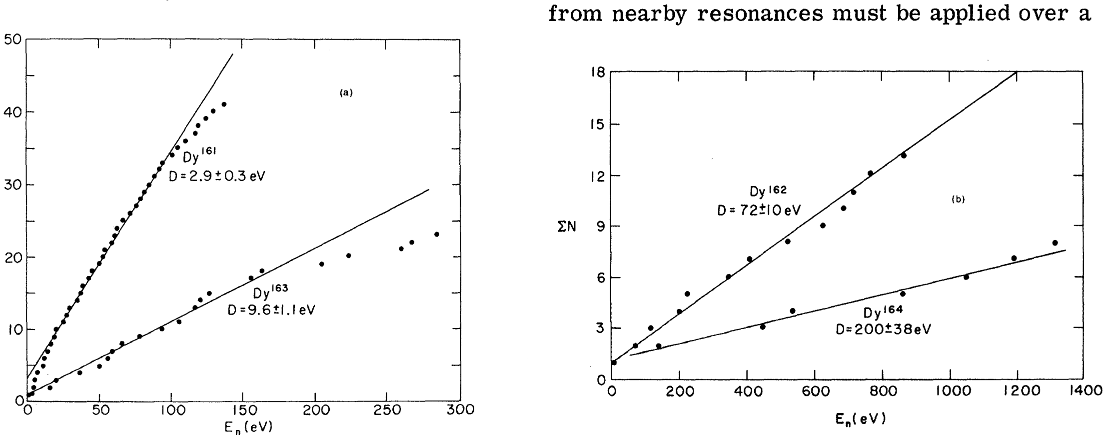


FIG. 5. The total number of neutron resonances is plotted versus incident neutron energy for $Dy^{161}$ and $Dy^{163}$ in (a), and for $Dy^{162}$ and $Dy^{164}$ in (b).

reasonably large energy interval.

One of the principal sources of error in such measurements is the effect of water absorbed in the powdered oxide sample. In a separate experiment,[16] the water contents of the oxide samples was found to be 0.39% by weight. The contribution from the absorbed water, as well as the oxide component in the $Dy_2O_3$ sample, were taken into consideration in extracting the potential scattering radius of these isotopes. The values are listed in column 6 of Table IV.

The variation of $R'$ with mass number is studied in Fig. 6 and is compared with the optical-model predictions as calculated by Jain.[17] A deformed-optical-model code with a surface-peaked term in the imaginary potential is used with parameters $V_0 = 49$ MeV, $W = 10$ MeV, $a = 0.52$ F, $b = 0.40$ F, and $R = 1.35A^{1/3}$. It is interesting to note that in this mass region, where the 4$S$ giant resonance attains a maximum, the ratio $R'/R$ is about 1.0. A radius constant $r_0 = 1.35$ F represents a good fit to the data.

### D. Thermal Cross Sections and Absorption-Resonance Integrals

Since no attempt was made to measure the thermal cross sections, it is useful to calculate these quantities from the parameters of resonances. The thermal cross section of $Dy^{164}$ is known[7] to be dominated by a bound level located at $E_0 = -1.89$ eV. Sher *et al.*[7] have measured the total and capture cross sections of $Dy^{164}$ in the region from thermal energy to 2.0 eV. An analysis of their data, using the INTTER code[18] indicates that a good fit to Sher's data is obtained by using a radiation width of 55 ± 3 meV; in good agreement with the value derived from Sher's reported results for $E_0, \Gamma_n^0$, and

TABLE III. Neutron-resonance parameters of the even-odd Dy isotopes, $Dy^{161}$ and $Dy^{163}$. Radiation widths of 114 ±10 and 109 ±8 meV are assumed in the analysis for $Dy^{161}$ and $Dy^{163}$ for resonances where no $\Gamma_\gamma$ is determined.

| $E_0$ (eV) | $2g\Gamma_n$ (meV) | $\Gamma_\gamma$ (meV) | $2g\Gamma_n^0$ (meV) | $E_0$ (eV) | $2g\Gamma_n$ (meV) | $\Gamma_\gamma$ (meV) | $2g\Gamma_n^0$ (meV) |
|---|---|---|---|---|---|---|---|
| | $Dy^{161}$ | | | | $Dy^{161}$ (*Continued*) | | |
| 2.72 ± 0.03 | 0.68 ± 0.07 | 119 ± 10[b] | 0.41 ± 0.05 | 92.5 ± 0.8[a] | 15.4 ± 4.6 | | 1.6 ± 0.3 |
| 3.68 ± 0.04 | 1.78 ± 0.18 | | 0.93 ± 0.09 | 94.4 ± 0.8[a] | 4.9 ± 1.5 | | 0.5 ± 0.2 |
| 4.33 ± 0.05 | 1.15 ± 0.17 | 80 ± 30 | 0.55 ± 0.08 | 100.7 ± 1.0 | 17.1 ± 3.1 | | 1.7 ± 0.3 |
| 7.74 ± 0.12 | 0.60 ± 0.12 | | 0.21 ± 0.04 | 104.5 ± 1.0 | 9.2 ± 1.5 | | 0.9 ± 0.1 |
| 10.40 ± 0.19 | 1.40 ± 0.3 | | 0.43 ± 0.09 | 109.9 ± 1.1 | 10.9 ± 2.2 | | 1.0 ± 0.2 |
| 10.91 ± 0.20 | 0.49 ± 0.15 | | 0.15 ± 0.05 | 111.9 ± 1.1 | 11.0 ± 2.2 | | 1.0 ± 0.2 |
| 14.33 ± 0.20 | 5.9 ± 0.6 | | 1.56 ± 0.16 | 117.0 ± 1.2 | 11.1 ± 2.8 | | 1.03 ± 0.26 |
| 16.84 ± 0.38 | 7.7 ± 1.3 | | 1.88 ± 0.34 | 119.7 ± 1.2 | 11.3 ± 2.8 | | 1.03 ± 0.26 |
| 18.47 ± 0.43 | 8.5 ± 0.9 | 110 ± 15 | 1.98 ± 0.21 | 123.7 ± 1.2 | 76 ± 19 | | 6.8 ± 1.0 |
| 20.23 ± 0.08 | 0.8 ± 0.2 | | 0.18 ± 0.06 | 130.4 ± 1.4 | 6.8 ± 1.6 | | 0.6 ± 0.1 |
| 25.08 ± 0.12 | 1.2 ± 0.1 | | 0.24 ± 0.02 | 137.6 ± 1.5 | 22.3 ± 4.4 | | 1.9 ± 0.4 |
| 28.84 ± 0.14 | 2.7 ± 0.2 | | 0.50 ± 0.04 | | $Dy^{163}$ | | |
| 29.73 ± 0.15 | 0.75 ± 0.11 | | 0.14 ± 0.02 | | | | |
| 35.50 ± 0.19 | 3.1 ± 0.2 | | 0.52 ± 0.03 | 1.71 ± 0.01 | 1.8 ± 0.2 | 103 ± 10[b] | 1.37 ± 0.15 |
| 37.64 ± 0.21 | 11.9 ± 1.6 | | 1.94 ± 0.26 | 16.20 ± 0.08 | 21.3 ± 0.8 | 115 ± 20 | 5.29 ± 0.20 |
| 38.38 ± 0.21 | 11.6 ± 1.6 | | 1.87 ± 0.29 | 19.55 ± 0.08 | 1.0 ± 0.1 | | 0.23 ± 0.02 |
| 43.02 ± 0.26 | 13.5 ± 2.0 | 150 ± 30 | 2.06 ± 0.31 | 35.72 ± 0.19 | 5.4 ± 1.0 | | 0.9 ± 0.17 |
| 44.85 ± 0.30 | 12.0 ± 1.1 | 93 ± 22 | 1.79 ± 0.16 | 50.0 ± 0.4 | 3.4 ± 0.4 | | 0.48 ± 0.05 |
| 50.8 ± 0.4 | 15.4 ± 4.0 | | 2.16 ± 0.56 | 55.7 ± 0.4 | 34.4 ± 3.0 | 114 ± 12 | 4.61 ± 0.40 |
| 51.8 ± 0.4 | 8.5 ± 2.0 | | 1.18 ± 0.28 | 58.8 ± 0.5 | 71.8 ± 4.0 | 107 ± 20 | 9.36 ± 0.52 |
| 54.9 ± 0.4 | 9.5 ± 1.3 | | 1.28 ± 0.18 | 66.0 ± 0.5 | 8.2 ± 1.3 | | 1.0 ± 0.2 |
| 59.1 ± 0.5 | 12.1 ± 1.1 | | 1.57 ± 0.14 | 78.8 ± 0.7 | 12 ± 2 | | 1.35 ± 0.22 |
| 61.1 ± 0.5 | 7.5 ± 0.8 | | 0.96 ± 0.10 | 93.9 ± 0.8 | 14 ± 2 | | 1.4 ± 0.1 |
| 63.3 ± 0.5 | 5.4 ± 0.7 | | 0.68 ± 0.09 | 105.9 ± 1.0 | 108 ± 15 | | 10.5 ± 1.5 |
| 66.4 ± 0.5 | 1.3 ± 0.6 | | 0.16 ± 0.07 | 117.0 ± 1.2 | 5 ± 2 | | 0.46 ± 0.19 |
| 72.3 ± 0.6 | 6.5 ± 0.8 | | 0.76 ± 0.09 | 120.0 ± 1.2 | 8 ± 2 | | 0.73 ± 0.18 |
| 76.5 ± 0.6 | 7.4 ± 0.7 | | 0.84 ± 0.08 | 126.4 ± 1.2 | 40 ± 7 | | 3.5 ± 0.6 |
| 79.4 ± 0.7 | 0.5 ± 0.1 | | 0.06 ± 0.01 | 154.8 ± 1.8 | 46 ± 7 | | 1.86 ± 0.58 |
| 81.8 ± 0.7 | 3.6 ± 0.4 | | 0.40 ± 0.04 | 163.3 ± 1.9 | 17 ± 3 | | 1.33 ± 0.23 |
| 84.6 ± 0.7 | 12.9 ± 1.5 | | 1.40 ± 0.2 | 204.7 ± 2.7 | 85 ± 20 | | 5.9 ± 1.4 |
| 88.3 ± 0.8 | 11.3 ± 1.4 | | 1.2 ± 0.2 | 223.6 ± 3.0 | 90 ± 20 | | 6.1 ± 1.3 |

[a]Pair of resonances not well resolved. [b]See Ref. 3.

TABLE IV. Summary of results of the rare-earth isotopes studied in the present and previous investigations. The third and fourth columns represent the spin of the target nucleus and the neutron separation energies of the resulting compound nucleus, respectively. The neutron strength functions as derived from (1) resonances in the energy interval indicated in the last column, and from (2) the average total cross section in the 5–15-keV region are listed in columns eight and nine, respectively. The remaining columns give the average level spacing $D$, the neutron scattering length $R'$, and the average radiation widths $<\Gamma_\gamma>$.

| Element | $A$ | $I$ | $B_n$ (keV) | $D$ (eV) | $R'$ (F) | $<\Gamma_\gamma>$ (MeV) | $10^4<g\Gamma_n^0>/D$ (from resonances) | $10^4<g\Gamma_n^0>/D$ (from $\sigma_{av}$) | Energy region (eV) |
|---|---|---|---|---|---|---|---|---|---|
| Gd | 155 | $\frac{3}{2}$ | 8527± 5 | 1.9± 0.2 | 6.7±1.5 | 108± 1[c] | 2.4±0.3 | 2.4±0.2 | 0.0268–240 |
| | 156 | 0 | 6347± 5 | 59 ±10 | 8.1±0.7 | 105±10 | 1.8±0.8 | 1.9±0.4 | 33.2–846 |
| | 157 | $\frac{3}{2}$ | 7929± 4 | 6.3± 0.6 | 4.9±1.3 | 107± 8 | 2.4±0.3 | 2.2±0.2 | 0.0314–600 |
| | 158 | 0 | 5942±10[a] | 92 ±15 | 6.5±1.0 | 108±20 | 1.6±0.6 | | 22.2–917 |
| | 160 | 0 | 5636±10[a] | 300 ±65 | 6.8±0.8 | | 2.5±1.3 | | 223–2680 |
| Dy | 161 | $\frac{5}{2}$ | 8193± 3 | 2.9± 0.3 | 8.9±0.8 | 114±10 | 1.8±0.4 | 1.85±0.15 | 2.72–138 |
| | 162 | 0 | 6270± 3 | 72 ±10 | 8.3±0.5 | 155±15 | 2.5±0.9 | 2.0 ±0.5 | 5.43–1250 |
| | 163 | $\frac{5}{2}$ | 7654± 3 | 9.6± 1.1 | 8.7±0.7 | 109± 8 | 1.7±0.3 | 1.7 ±0.2 | 1.71–350 |
| | 164 | 0 | 5715± 2 | 200 ±38 | 7.7±0.8 | 55± 3 | 1.2±0.5 | | −1.89–2850 |
| Er | 162 | 0 | 6840±90 | 6.9± 1.2 | 8.1±0.9 | | 2.1±0.7 | 2.1 ±0.6 | 5.48–140 |
| | 164 | 0 | 6645±40 | 20 ± 3 | 9.2±0.8 | | 1.6±0.5 | 1.4 ±0.3 | 7.92–240 |
| | 166 | 0 | 6436± 3 | 49 ± 7 | 7.7±0.9 | 88± 7[d,e] | 1.9±0.7 | | 15.6–603 |
| | 167 | $\frac{7}{2}$ | 7764± 3 | 3.7± 0.4 | 9.9±0.9 | 88± 1[c] | 2.6±0.4 | 1.7 ±0.2 | 0.46–315 |
| | 168 | 0 | 5997±12 | 125 ±19 | 6.6±0.8 | 81±10[e] | 1.4±0.7 | | 79.9–1410 |
| Yb | 170 | 0 | 6616± 3[b] | 37 ± 6 | 7.3±0.6 | | 2.5±0.7 | 2.4 ±0.3 | 8.13–990 |
| | 171 | $\frac{1}{2}$ | 8023± 3[b] | 6.5± 0.8 | 6.3±0.6 | 73± 5 | 1.6±0.3 | 1.2 ±0.2 | 7.93–354 |
| | 172 | 0 | 6367± 3[b] | 62 ±10 | 6.3±0.8 | | 0.8±0.3 | 1.6 ±0.4 | 140–818 |
| | 173 | $\frac{5}{2}$ | 7464± 3[b] | 8.4± 1.0 | 7.4±0.6 | 74± 6 | 1.6±0.3 | 1.9 ±0.2 | 4.51–492 |
| | 174 | 0 | 5822± 5 | | 6.4±1.0 | | | | |
| | 176 | 0 | 5565±16 | 284 ±53 | 7.0±0.6 | | 1.7±0.5 | | 149–5787 |

[a]P. O. Tjom and B. Elbeck, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. 36, No. 8 (1967).
[b]A. I. Namenson and J. C. Ritter, Phys. Rev. 183, 983 (1969).
[c]See Ref. 37.
[d]See Ref. 34.
[e]See Ref. 35.

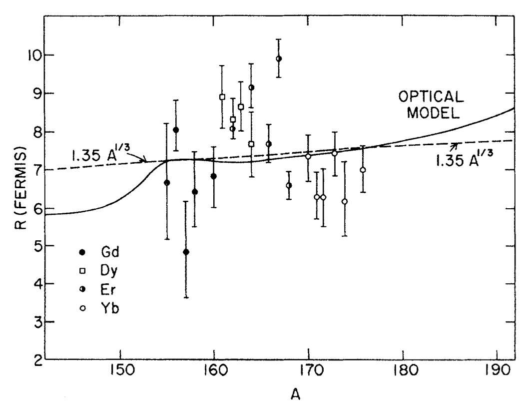


FIG. 6. Variation of the neutron scattering radius with mass number is shown for the rare-earth isotopes studied in the present and previous works. Also shown is the optical-model prediction and values based on the relation $R = 1.35A^{1/3}$ F.

$\sigma_0\Gamma^2$. [It must be pointed out here that the value of $\Gamma$ reported by Sher *et al.* (0.166 eV) is not derived from curve fitting, but is based on an assumed value for $\Gamma_\gamma$ of 0.110 eV. This value of $\Gamma_\gamma$ is not consistent with Sher *et al.*'s data and should be ignored.[19]]

In addition, we have calculated the absorption-resonance integral, $I_\gamma$, scattering, absorption, and total cross sections, $\sigma_s$, $\sigma_\gamma$, and $\sigma_t$, respectively. We used: (a) the resonance parameters of Tables II and III; (b) the scattering radii, $R'$, and average radiation widths of Table IV; and (c) the bound levels of $Dy^{161}$ and $Dy^{163}$ as determined by Danelyan *et al.*[8] For comparison we list in columns 3, 6, and 8 of Table V the experimental values of the[11] thermal-absorption cross section, the[20] absorption-resonance integrals, $I_\gamma$, and the[21] total cross section, $\sigma_t$, at a neutron energy of 0.07 eV.

For completeness, we adopted the resonance parameters of Vertebny *et al.*[22] to calculate $\sigma_\gamma$ and $I_\gamma$ for $Dy^{156}$ and $Dy^{158}$. As shown in the table, the thermal cross section of $Dy^{162}$ is accounted for in terms of contributions from positive-energy resonances and is in agreement with Danelyan's experimental value. The calculated absorption-resonance integrals are in satisfactory agreement with the accepted experimental values.[11] It is of interest to point out that, for $Dy^{160}$, both $\sigma_\gamma$ at $E_n = 0.0253$ eV and $\sigma_t$ at $E_n = 0.07$ eV are in excellent agreement with the calculated values if $\Gamma_\gamma = 85 \pm 14$ meV. The error in this quantity is derived from that in the experimental values. Most of the contribution to the scattering cross section of natural dysprosium is due to $Dy^{164}$. If the isotopic-scattering cross sections are compounded, a value of 117 b is obtained, which is in reasonable agreement with an early measurement of Brockhouse,[23] which yielded 100 b.

### E. *s*-Wave, Neutron Strength Functions and Radiation Widths

In the resolved energy region, the *s*-wave neutron strength function is derived from the reduced neutron widths. This procedure is illustrated for $Dy^{161}$, $Dy^{162}$, and $Dy^{163}$ in Figs. 7(a), (b), and (c), which gives the *s*-wave neutron strength functions for these isotopes. The values thus derived are $1.8 \pm 0.4$, $2.5 \pm 0.9$, and $1.7 \pm 0.3$, all in units of $10^{-4}$. Similar analysis for $Dy^{164}$ in the energy range from $-1.89$ to 2850 eV yields a value of $(1.2 \pm 0.5) \times 10^{-4}$. In column 10 of Table IV we have indicated the energy interval from which the strength functions are extracted. The neutron strength functions are also derived from the unresolved energy region using the average cross sections. The values thus obtained are listed in column 9 of Table IV. We have included in the same table our previous results[2,16,24] on the rare-earth isotopes. The agreement between the two values of the neutron strength functions as derived by the two methods is very satisfactory. The strength functions are plotted in Fig. 8 and are compared with the rotational vibrational optical-model predictions of Buck and Perey[25] as calculated by Jain.[17]

Inspection of Table IV reveals several interesting features about the *s*-wave neutron strength functions in this mass region.

(1) The strength functions of $Dy^{162}$ and $Dy^{164}$ are similar to the corresponding isobars $Er^{162}$ and $Er^{164}$.

(2) The strength functions of the odd isotopes of a particular element are identical within the statistical accuracy of the data.

(3) For the Dy isotopes, the data suggest a correlation between *s*-wave neutron function and radiation widths. This point will be dwelt upon later in the discussion.

(4) Despite the statistical accuracy of the strength-function values for the even isotopes, there appears to be a nearly consistent trend of decrease of $S$ with increasing $A$. This is particularly evident for the three pairs of isotopes ($Dy^{162}$, $Dy^{164}$), ($Er^{162}$, $Er^{164}$), and ($Yb^{170}$, $Yb^{172}$).

In order to improve the statistical accuracy of the strength-function values, we combined the two results obtained in the two different energy intervals. These are listed in Table VI along with other results[26] near the same mass region. Fuketa and Harvey[26] have noted a similar behavior for the even-even target nuclei $Hf^{172}$, $Hf^{174}$, and $Hf^{176}$, but not for the even-odd target nuclei $Hf^{177}$ and $Hf^{179}$, thus substantiating our findings. The results of the present experiment and those of Fuketa and Harvey are reminiscent of the systematics of the strength functions of the tin isotopes.[27-29] Such a type of fluctuation in the strength functions

TABLE V. Comparison between calculated and experimental values in barns of the thermal absorption, scattering, and total cross sections and absorption-resonances integrals of the Dy isotopes.

| Natural abundance | Isotope | $\sigma_\gamma$ expt.[a] | $\sigma_\gamma$ calc. | $\sigma_s$ calc. | $I_\gamma$ expt.[b] | $I_\gamma$ calc. | $\sigma_t$ (0.07 eV) expt.[c] | $\sigma_t$ (0.07 eV) calc. |
|---|---|---|---|---|---|---|---|---|
| 0.052 | $Dy^{156}$ | | 2.9 | 6.1 | | 137 | | 7.9 |
| 0.090 | $Dy^{158}$ | 96 ± 20 | | | 100 ± 50 | | | |
| 2.29 | $Dy^{160}$ | 55 ± 9 | 55 | 3.3 | | 846 | 36.4 ± 6.0 | 36.4 |
| 18.88 | $Dy^{161}$ | 600 ± 50 | 600 | 31 | 1190 ± 150 | 1074 | 366 ± 13 | 380 |
| 25.53 | $Dy^{162}$ | 160 ± 27 | 203 | 0.49 | 2575 ± 300 | 2728 | 111 ± 6 | 124 |
| 24.97 | $Dy^{163}$ | 125 ± 20 | 151 | 6.1 | 1650 ± 200 | 1681 | 78 ± 12 | 96.6 |
| 28.18 | $Dy^{164}$ | 2700 ± 200 | 2562 | 388 | 380 ± 30 | 318 | 1880 ± 30 | 1843 |

[a]See Ref. 11. [b]See Ref. 20. [c]See Ref. 21.

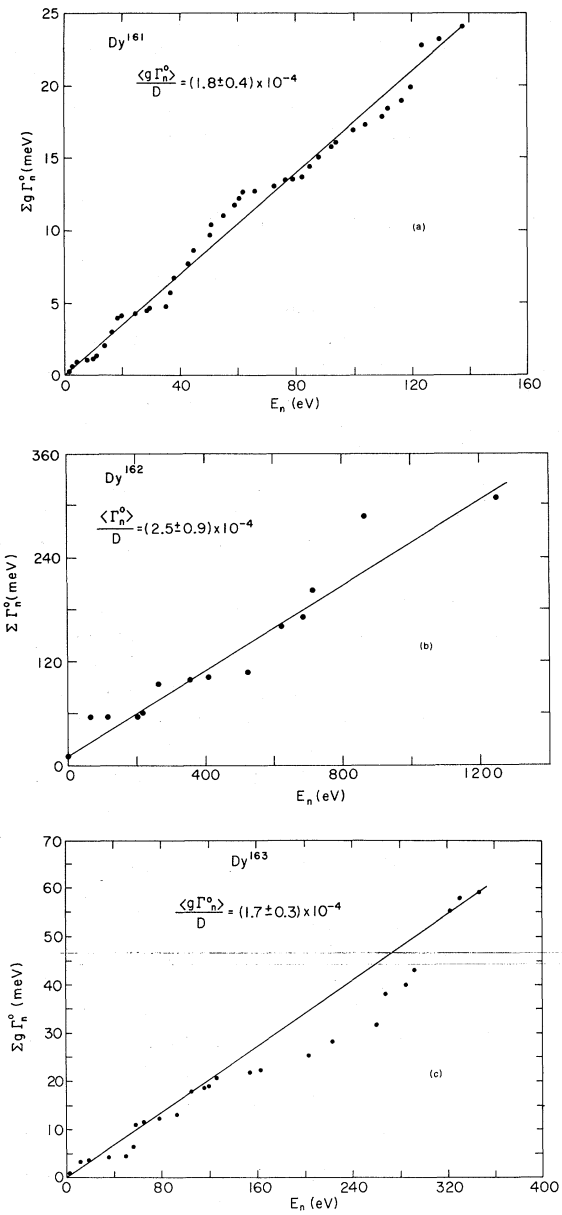


FIG. 7. Cumulative reduced neutron widths are plotted versus incident neutron energies for $Dy^{161}$, $Dy^{162}$, and $Dy^{163}$ in (a), (b), and (c), respectively, to obtain the neutron strength functions per spin state.

of the even-even tin isotopes has been described[30] successfully in terms of the two-particle-one-hole states (2p-1h), also known as the doorway states. However, no calculation for the even-odd tin isotopes have been carried out yet to find out whether the same tendency persists; i.e., the decrease of $S$ with increasing $A$. The doorway-state concept as developed by Feshbach, Kerman, and Lemmer[31] suggests an explanation as to why fluctuations in the strength functions of the odd isotopes are not

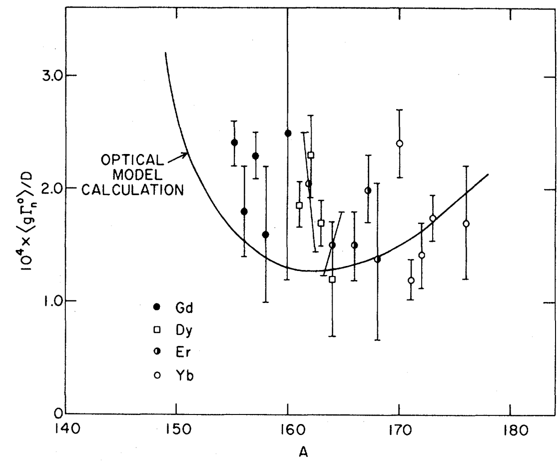


FIG. 8. The measured $s$-wave neutron strength functions in the rare-earth region are compared with the predictions of the rotational-optical-model code of Buck and Perey. See text for the parameters of the potential well.

observed here. For these nuclei, the damping width is large, because of a higher density of compound states; a circumstance which would hinder the chance of observing the doorway state. Actual quantitative calculations are needed to find out whether the effect of the 2p-1h states in the mass region around $A = 162$ is important. Another possible explanation for such systematics can be based on a suggestion of Lane[32] who introduced an additional term to the complex potential of the form:

$$V = V_0 + \vec{t}\cdot(\vec{T}V_1/A),$$

where $t$ and $T$ designate the isobaric-spin vectors of the incident particle and target nucleus of mass $A$, respectively. This term provides a good description of analog states.

For incident neutrons, this term becomes

$$V = V_0 + \tfrac{1}{4}(N-Z)V_1/A\ .$$

TABLE VI. Variation of neutron strength functions of the even-even target nuclei with mass number.

| Isotope | $S^0$ |
|---|---|
| $Dy^{162}$ | 2.3 ±0.5 |
| $Dy^{164}$ | 1.2 ±0.5 |
| $Er^{162}$ | 2.1 ±0.4 |
| $Er^{164}$ | 1.5 ±0.3 |
| $Yb^{170}$ | 2.4 ±0.4 |
| $Yb^{172}$ | 1.35 ±0.25 |
| $Hf^{174}$ [a] | 2.8 ±1.0 |
| $Hf^{176}$ [a] | 1.4 ±0.6 |
| $Hf^{178}$ [a] | 1.1 ±0.6 |

[a] See Ref. 6.

The magnitude of $V_1$ is estimated to be about 25 MeV. If such a formalism applies to the description of the present data, it is not clear to us why the odd isotopes do not exhibit the same behavior. It may be that either a spin-spin coupling term in the optical potential would obscure the effect, or, as suggested by Satchler,[33] that $V_1$ depends on the nuclear shell structure. With the object of searching for the presence of such an isobaric-spin term, Lynn[34] analyzed the available strength-function data for the even-even isotopes in the mass region around the 3*S* giant resonance, but he did not detect any systematics in the results. The variation of $S^0$ with $A$ is so rapid in this mass region that it would tend to cloud the results. Our results pertain to nuclei which lie in the 4*S* giant resonance where the variation of $S^0$ with $A$ is slight. It is noteworthy that the latter point applies to the tin isotopes, too.

To study the systematics of radiation widths of resonances we have plotted our present and previous results in Fig. 9, along with recent measurements of others.[35-38] As represented in Fig. 9, the radiation widths of Dy isotopes define a structure with a peak centered at $A = 162$. The curve is based on Cameron's calculation of radiation widths in which

$$\Gamma_\gamma = 5.2A^{2/3}b^4(1+2bU^{-1/2})(U^2 - \tfrac{10}{3}bU^{3/2} + 5b^2U - \tfrac{35}{9}b^3U^{1/2} + \tfrac{35}{27}b^4),$$

where $b = 5.97/(\bar{J}_N + \bar{J}_Z + 1)^{1/2}A^{1/3}$,

$$U = B_n - \Delta .$$

$B_n$ is the neutron separation energy, $U$ the effective excitation energy corrected for pairing energy, and $\bar{J}_N$ and $\bar{J}_Z$ are the effective total angular momenta of single-particle states near the Fermi surface. For a compound nucleus, the pairing energies are given by:

$$\begin{aligned} \Delta &= \delta_n + \delta_p && \text{even-even},\\ &= \delta_p && \text{even-odd},\\ &= \delta_n && \text{odd-even},\\ &= 0 && \text{odd-odd}. \end{aligned}$$

The neutron and proton pairing energies have been taken from the work of Nemirovsky and Adamchuk[39] and the neutron separation energies from Ref. 20, except where otherwise indicated in Table IV. The relation for radiation widths reproduced qualitatively the peaks at $A = 138$ ($N = 82$) and $A = 208$ ($N = 126$) due to major shell closure near magic numbers; i.e., large neutron separation energies. However, it was deficient in predicting the structure observed in the Dy isotopes and illustrated in Fig. 9.

Cameron[6] noted that the peak in the radiation width at $A = 162$ occurs at the same position as the 4*S* single-particle states. He suggested that this could possibly be due to large admixtures of single-particle wave functions in the intial and final states for the radiative process. To pursue the matter further, we plotted in Fig. 10 the *s*-wave neutron strength functions against radiation widths. As noted, the correlation between these two quantities

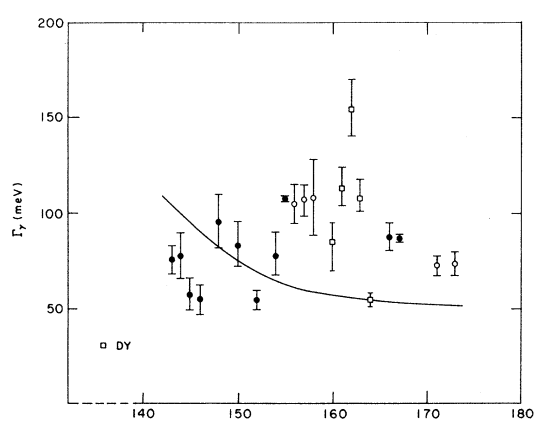


FIG. 9. Variation of nuclear radiation widths with mass number. The solid curve is based on Cameron's relation (see text). Note that radiation widths of Dy isotopes define a fine structure which is not accounted for in terms of Cameron's relation.

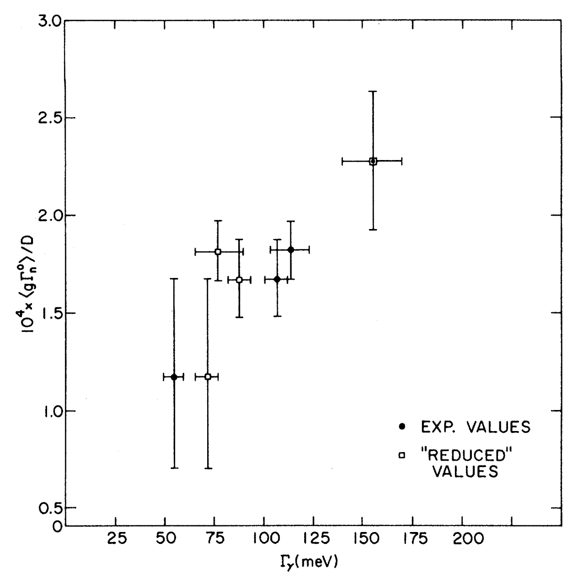


FIG. 10. Correlation of total radiation width with *s*-wave neutron strength functions is shown for the Dy isotopes. A large radiation width (of $Dy^{162}$) seems to be associated with a large *s*-wave neutron strength function.

is very high. However, the observed radiation widths must be corrected for excitation energies and shell effects. These factors have been eliminated from the observed radiation width with the aid of Cameron's equation.

The results thus treated are arbitrarily normalized such that $Dy^{162}$ has a radiation width equal to 155 meV. As shown in Fig. 10, two interesting points emerge: (a) $Dy^{162}$ still has an anomalous radiation width, and (b) a large radiation width of $Dy^{162}$ is still associated with a large $s$-wave neutron strength function. It will be of great interest to investigate the $\gamma$-ray spectra from neutron capture in various resonances of these isotopes to search for a possible direct capture component in the reaction mechanism in these nuclei. In addition, it will be fruitful to study the correlation between reduced neutron widths and partial radiation widths in order to obtain more insight into this question.

## V. SUMMARY AND CONCLUSION

The comparatively high level density of some of the even-even target nuclei, considered in the present and in previous investigations, made it possible to apply the average-total-cross-section method in the keV region to derive the $s$-wave neutron strength functions. The improved statistical accuracy of $S^0$, coupled with the observations of a general persistent trend for the even-even target nuclei, enabled us to detect a decrease of $S^0$ with $A$. This is not consistent with the optical-model calculations in this mass region. In addition, the variation of total radiation width with mass number for the Dy isotopes defines a fine structure with a peak centered at $A = 162$, a behavior which is not explainable in terms of Cameron's calculations[14] as based on the statistical model. These two observations: (1) the decrease of $S^0$ with increasing $A$ for the even-even target nuclei; and (2) the relative enhancement of the radiation width of $Dy^{162}$, suggest the presence of a doorway state coming into "focus" in the compound nucleus, $Dy^{163}$. Recently, Bartholomew *et al.*[40] pointed out the importance of the doorway state in the deexcitation process in $(n, \gamma)$ and $(d, p\gamma)$ reactions. A neutron interacting with a nucleus would form an intermediate state (2p-1h) which would deexcite by emission of a $\gamma$ ray when a particle and a hole combine. However, quantitative and detailed calculations are required to confirm these ideas. On the other hand, the apparent correlation of $\Gamma_\gamma$ with $S^0$ indicates that single-particle effects may be present here. It is evident that a detailed study of $\gamma$-ray spectra due to neutron capture in these nuclei is necessary in order to distinguish between these possibilities. Furthermore, the present results demonstrate the need for further investigations of the systematics of neutron resonances in the mass region where the variation of $S^0$ with $A$ is not strong.

## ACKNOWLEDGMENTS

The authors gratefully acknowledge the assistance of Jean Domish and I. W. Cole in performing analysis of the data and calculations connected with this research.

*This work was supported by the U. S. Atomic Energy Commission.

[1]R. E. Chrien and S. F. Mughabghab, in Proceedings of Symposium, Antwerp, The Netherlands, 1965, Nuclear Structure Study with Neutrons, edited by M. Nève de Mévergnies, P. Van Assche, and J. Vervier (North-Holland Publishing Co., Amsterdam, The Netherlands, 1966), p. 524; R. E. Chrien, S. F. Mughabghab, M. R. Bhat, and A. P. Jain, Phys. Rev. Letters 24B, 573 (1967).

[2]S. F. Mughabghab and R. E. Chrien, Phys. Rev. 180, 1131 (1969).

[3]R. L. Zimmerman, Bull. Am. Phys. Soc. 2, 42 (1957).

[4]A. G. W. Cameron, Can. J. Phys. 35, 666 (1957).

[5]T. D. Newton, Can. J. Phys. 34, 804 (1956).

[6]A. G. W. Cameron, Can. J. Phys. 37, 322 (1959).

[7]R. Sher, S. Tassan, E. V. Weinstock, and A. Hellsten, Nucl. Sci. Eng. 11, 369 (1961).

[8]L. S. Danelyan, Yu. V. Adamchuk, S. S. Moskalev, M. I. Pevzner, and S. S. Yastrebov, At. Energy. (USSR) 16, 56 (1964) [transl.: Soviet J. At. Energy 16, 58 (1964)].

[9]J. Brunner and F. Widder, in Proceedings of the Conference on Nuclear Data, Microscopic Cross Sections and Other Data Basic for Reactors, Paris, 1966 (International Atomic Energy Agency, Vienna, Austria 1967), Vol. 1, p. 61.

[10]J. E. Lynn, The Theory of Neutron Resonance Reactions (Clarendon Press, Oxford, England, 1968), p. 319.

[11]M. D. Goldberg, S. F. Mughabghab, S. N. Purohit, B. A. Magurno, and V. M. May, Brookhaven National Laboratory Report No. 325, 1966 (unpublished), Vol. IIC, 2nd ed., Suppl. 2.

[12]M. R. Bhat and R. E. Chrien, Phys. Rev. 155, 1362 (1967).

[13]S. E. Atta and J. A. Harvey, J. Soc. Ind. Appl. Math. 10, 617 (1962); see also Oak Ridge National Laboratory Report No. ORNL 3205, 1961 (unpublished).

[14]D. J. Hughes, J. Nucl. Energy 1, 237 (1955).

[15]R. E. Chrien, Phys. Rev. 141, 1129 (1966).

[16]S. F. Mughabghab, R. E. Chrien, and M. R. Bhat, Phys. Rev. 162, 1130 (1967).

[17]A. P. Jain, Nucl. Phys. 50, 157 (1964).

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

[19]R. Sher, private communication.

[20]M. K. Drake, private communication. See also M. D. Goldberg and J. A. Harvey, American Institute of Physics Handbook (McGraw-Hill Book Company, Inc., New York, 1970), 3rd ed.

[21]H. R. Child, L. J. Raubenheimer, W. C. Khoeler, and R. M. Moon, Phys. Rev. 174, 1553 (1968).

[22]V. P. Vertebnyi, A. I. Kal'chenko, M. V. Pasechnik, Zh. I. Pisanko, and V. K. Rudyshin, Ukr. Fiz. Zh. Akad. Nauk Ukr. SSR 13, 2085 (1968) [transl.: Ukrainian Phys. J. 13, 1492 (1969)].

[23]B. N. Brockhouse, Can. J. Phys. 31, 432 (1953).

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

[25]B. Buck and F. Perey, Phys. Rev. Letters 8, 444 (1962).

[26]T. Fuketa and J. A. Harvey, Oak Ridge National Laboratory Reprot No. ORNL 3778, 1964 (unpublished), p. 38.

[27]F. A. Khan and J. A. Harvey, Bull. Am. Phys. Soc. 7, 289 (1962). See also T. Fuketa, F. A. Khan, and J. A. Harvey, Oak Ridge National Laboratory Report No. ORNL 3425 (1963), p. 36.

[28]Yu. V. Adamchuk, S. S. Moskalev, and G. V. Muradyan, Yadern. Fiz. 3, 801 (1966) [transl.: Soviet J. Nucl. Phys. 3, 589 (1966)].

[29]It is interesting to point out that recent reported results from Saclay [H. Tellier, M. Alix, and J. Dabbs, Compt. Rend. B269, 269 (1969)] indicate that there is a decrease of $S^0$ with increasing $A$ for the Te isotopes.

[30]C. Shakin, Ann. Phys. (N.Y.) 22, 373 (1963).

[31]H. Feshbach, A. K. Kerman, and R. H. Lemmer, Ann. Phys. (N.Y.) 41, 230 (1967).

[32]A. M. Lane, Phys. Rev. Letters 8, 171 (1962).

[33]G. R. Satchler, Isospin in Nuclear Physics, edited by D. H. Wilkinson (North-Holland Publishing Co., Amsterdam, The Netherlands, to be published).

[34]Lynn, see Ref. 10, p. 273.

[35]H. Liou, H. Camarda, G. Hacken, W. W. Havens, Jr., F. Rahn, J. Rainwater, M. Slagowitz, and S. Wynchank, Bull. Am. Phys. Soc. 14, 495 (1969), and private communication.

[36]E. N. Karzhavina, B. B. Popov, and Yu. S. Yazvetskii, Yadern. Fiz. 7, 225 (1968) [transl.: Soviet J. Nucl. Phys. 7, 161 (1968)].

[37]E. N. Karzhavina, Nguyen Nguyen Fong, A. B. Popov, and A. I. Taskaev, Yadern. Fiz. 8, 639 (1968) [transl.: Soviet J. Nucl. Phys. 8, 371 (1969)].

[38]H. B. Moller, F. J. Shore, and V. L. Sailor, Nucl. Sci. Eng. 8, 183 (1960).

[39]P. E. Nemirovsky and Yu. V. Adamchuk, Nucl. Phys. 39, 551 (1962).

[40]G. A. Bartholomew, E. D. Earle, A. J. Ferguson, and I. Bergvist, Phys. Letters 24B, 47 (1967); E. D. Earle, M. A. Lone, and G. A. Bartholomew, Bull. Am. Phys. Soc. 14, 515 (1969).

# Search for the $0^+$ Member of the Two-Phonon Triplet in $^{110}$Cd

James R. Van Hise* and Miquel C. Kelley†

Andrews University,‡ Berrien Springs, Michigan

and

Robert G. Lanier§ and Noah R. Johnson

Oak Ridge National Laboratory,‖ Oak Ridge, Tennessee

(Received 31 December 1969)

Levels in $^{110}$Cd have been studied through the decay of $^{110g}$Ag($1^+$) using NaI(Tl) and Ge(Li) detectors. The following $\gamma$-ray energies (intensities in parentheses) were observed: 657.8 ± 0.2(100), 815.6 ± 0.3(0.98), 1125.9 ± 0.3(0.36), 1186.4 ± 0.7(0.056), 1421.8 ± 1.3(0.044), 1475.8 ± 1.3(0.11), 1630.0 ± 1.2(0.048), 1674.2 ± 0.9(0.15), and 1783.3 ± 1.3(0.17) keV. Coincidence measurements performed with a NaI(Tl)-Ge(Li) system showed peaks at 816 and 1126 keV in coincidence with the 657.8-keV line. The 815.6-keV peak in the singles spectrum is a doublet composed of the 818.00-keV component depopulating the $2^+$ state at 1475 ± 0.05 keV and a 815.5-keV $\gamma$ ray. It is proposed that the low-energy component depopulates the two-phonon, $0^+$ level at 1473.2 ± 0.3 keV. A level at 1783.6 ± 0.3 keV is also assigned and estimates of log$ft$ values to all levels are given. Using a multichannel analyzer in the multiscalar mode, the half-life of $^{110g}$Ag was measured as 24.7 ± 0.7 sec.

## I. INTRODUCTION

There exists much interest in understanding the nature of the low-lying states of medium-weight even-even nuclei. These states show collective properties, many of which are described by the quadrupole vibrator model. At about twice the energy of the first excited $2^+$ state in these nuclei, there are frequently observed $2^+$ and $4^+$ members of the expected triplet of levels. However, the $0^+$ member of this triplet seems much more elusive, with the result that its properties