Radiation Widths of Bound Nuclear Levels in the Vicinity of the Neutron Threshold

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The radiation widths of bound nuclear levels excited by (γ, γ') reactions in nuclei ^{139}La, ^{130}Te, ^{120}Sn, ^{86}Sr, ^{80}Se, and ^{66}Zn have been measured. The present results together with results published by other authors using (γ, γ') reactions are summarized and compared with similar results obtained in capture reactions of thermal and resonance neutrons. The expected properties of the nuclear levels obtained by extrapolation of the giant-dipole resonance to lower energies are compared with the present experimental data. The fluctuation in partial radiative widths from these bound levels is shown to be compatible with the Porter-Thomas distribution.

I. INTRODUCTION

The excitation and consequent transitions from highly excited bound nuclear levels permit a study of the various nuclear properties of such levels, including the energy, spin, parity, and the total and partial radiative widths.

While unbound nuclear levels can be populated using particle-capture reactions (e.g., neutron-resonance capture), highly excited bound levels in stable nuclei can be conveniently reached through the electromagnetic interaction between the photons of the incident γ beam and the nucleus.

The nuclear level spacing is usually small in the vicinity of the neutron threshold, and requires an incident radiation with a narrow energy band (a few eV's) to permit the excitation of isolated levels. Such nearly monoenergetic γ lines are obtained in the (n, γ) reaction using thermal neutrons. This method has been used extensively in the last few years to excite bound levels in a wide variety of nuclei.[1-17]

Although this method is based on an accidental overlap in energy between one of the lines in the spectrum of the incident radiation and a level in the target nucleus, a large number of resonant levels have been detected. However, the present unavailability of continuous energy variation of the incident γ rays does not permit as yet a systematic study of a particular nucleus, as is the case in resonant neutron capture, except in a few cases where by chance several levels have been excited in a single nucleus.

The results obtained in the present work, together with those previously published are discussed in this paper.

A reasonable assumption, partly confirmed by experiment, is made with respect to the character of the high-energy primary transitions from the resonant levels, these being assumed to be predominantly of dipole nature. Measurements of the linear polarization of the scattered radiation were carried out in a few cases,[18] thus permitting the determination of the electric or magnetic nature; however at present such a measurement is in most cases a difficult task due to the low intensity of the scattered radiation. A comparison of the reduced partial widths with those of known $E1$ and $M1$ transitions permits, in some cases, the assignment of a particular transition as being of electric or magnetic dipole nature. Moreover, all of the reduced partial radiative widths obtained in this work are found to fall within the limits observed for known dipole transitions, thus following the systematics determined from earlier work.

As discussed by Axel,[19] one can consider the properties of the nuclear levels in the 7-MeV energy region as being governed by the electric giant dipole resonance of the photonuclear reaction. A comparison of the cross sections for nuclear photoabsorption and the values of the strength function calculated according to this model shows a fair agreement with the experimental data of Reibel and Mann[20] and of Hayward and Fuller.[21] While Axel's prediction concerns the behavior of the various parameters averaged over an energy interval ΔE, it can be anticipated that the corresponding experimental values as obtained for single levels could considerably depart from the predicted values because of their statistical nature. It was actually observed that if Axel's suggestion is correct then the fluctuations of the partial radiative widths are considerable.

The fluctuations of partial reaction widths in nuclear reactions were analyzed and discussed by Porter and Thomas.[22] Owing to the complexity of the wave functions describing highly excited nuclear levels, it can be shown that under plusible conditions the matrix elements describing the transitions from such a level to all possible final states follow a normal distribution with the mean equal to zero. In this case the distribution of the partial radiative widths (normalized to the mean value) follows a χ^2 distribution with ν degrees of freedom, this being equal to 1 if only one reaction exit channel is open. This type of distribution was found to give a good description of the results obtained in elastic neutron scattering and many resonance-neutron-capture reactions in the unbound energy region, while there is as yet no direct experimental evidence as to whether the Porter-Thomas distribution applies to the partial radiative widths in the bound region below the neutron-emission threshold. This problem cannot be investigated directly by the present technique because of the random character of the excitation of the resonant levels; therefore we propose an indirect method to clarify this question. This test, being assumed independent of the

TABLE I. Total and ground-state radiation widths of the resonant levels together with the reduced widths of the ground-state transitions.

Nucleus	J^π	Energy of resonant level (MeV)	Total width Γ (eV)	Ground-state transition width Γ_0 (eV)	Level spacing D using Cameron's formula (Refs. a, b) (eV)	K_{E1} Reduced width (10^{-3} eV MeV^{-4})	K_{M1}	10^5C
^{209}Bi		7.416	0.23 ±0.17	0.14 ±0.09 [c]	250	39.0	1373	1.97
^{208}Pb	1^+	7.285	0.80 ±0.03	0.80 ±0.03 [d]	1900 (5800)	29.4	1030	4.65
^{205}Tl	$\frac{1}{2}^{(-)}$	7.647	~1.2	~1.0 [c]	470	13.7	4760	6.70
^{150}Sm [e]	1	8.998	6.5 ±0.5	1.43 ±0.30 [f]	4 (3)	17.4×10^3	490×10^3	3450
^{141}Pr	$\frac{5}{2}^{(-)}$	7.632	0.133±0.023	~0.6 [g]	60	83.0	2228	8.57
^{141}Pr	$\frac{7}{2}^{(-)}$	6.115	0.050±0.010	0.028±0.008 [f]	175	25.4	695	5.60
^{139}La	$\frac{7}{2}^{(-)}$	6.760	0.070±0.040	0.011±0.006 [f]	145 (135)	9.1	245	1.26
^{139}La	$\frac{9}{2}^{(-)}$	6.418	0.050±0.020	0.043±0.017 [f]	160 (145)	37.7	1014	7.15
^{139}La	$\frac{9}{2}^{(-)}$	6.115	0.050±0.025	0.022±0.011 [f]	210 (230)	17.2	458	3.54
^{130}Te	1	7.538	0.24 ±0.06	0.05 ±0.01 [f]	300	15.1	389	5.72
^{120}Sn	1	7.696	0.12 ±0.03	0.07 ±0.02 [f]	165 (115)	38.2	930	16.20
^{112}Cd	$1^{(-)}$	7.632	0.13	0.06 [h]	130 (75)	45.2	1050	20.00
^{90}Zr	1	8.496	2.10 ±0.53	1.68 ±0.02 [c]	1280	106.0	2141	66.00
^{86}Sr	1	7.820	0.10 ±0.05	0.030±0.015 [f]	980	3.2	64	2.64
^{80}Se	1	7.820	0.09 ±0.02	0.030±0.007 [f]	680	7.4	138	4.55
^{75}As	$\frac{1}{2}^{(-)}$	7.646	0.36 ±0.10	0.041±0.011 [i]	350	14.8	263	8.14
^{66}Zn	1	7.696	0.21 ±0.04	0.10 ±0.02 [f]	2100	6.4	104	8.95
^{66}Zn	1	7.368	0.31 ±0.03	0.22 ±0.02 [j]	2600	12.8	210	19.68
^{62}Ni	1	7.646	0.48	0.31 [h]	4000	11.1	175	17.84

[a] See Ref. 29.
[b] Figures in parentheses refer to energy extrapolation of D by the Couteur's formula (see paragraph III).
[c] See Ref. 15.
[d] See Ref. 3.
[e] This is an unbound level, lying about 1 MeV above the neutron threshold having a total radiative width of 5 eV.
[f] Present work.
[g] See Ref. 16.
[h] R. Moreh and A. Nof, Bull. Am. Phys. Soc. 13, 1451 (1968). Note that more recent results by these authors (private communication) give somewhat lower values.
[i] R. Moreh, private communication.
[j] N. Shikazono and Y. Kawarasaki, J. Phys. Soc. Japan 27, 273 (1969).

choice of a particular nucleus, makes use of the results obtained in different nuclei using the (γ, γ') reaction. Application of this procedure to the experimental results shows that the Porter-Thomas distribution is fully compatible with the observed fluctuations in partial radiation widths in the energy region investigated.

II. EXPERIMENTAL PROCEDURE AND RESULTS

The experimental facilities for resonance scattering of γ rays at the IRR-1 and IRR-2 reactors have been described elsewhere.[3,5] In the present work a search for resonant levels was carried out resulting in about 30 levels detected in various nuclei using a nickel (n, γ) source. Most of these levels gave a weak effect and the low intensity of the scattered γ rays did not permit a thorough study of the nuclear parameters. Relatively strong effects were obtained using natural targets of tellurium[5] (at least three resonant levels were observed), tin (two levels observed), strontium, selenium, and zinc. Using sources of chlorine and titanium, relatively strong-intensity scattering was observed using a natural lanthanum target.[6] The experimental method consists of measurements of the effective elastic scattering cross section, temperature dependence of the intensity of scattered radiation, and in a few cases, a measurement of the self-absorption of the particular γ line. These measurements provide information for the calculation[3] of the total and partial radiative widths of the resonant levels, making use of the experimentally determined branching ratios of the inelastic transitions to low-lying levels as seen from the spectrum of the scattered radiation.

The measurements were carried out using both lithium-drifted germanium and sodium iodide scintillation detectors. The spectra were obtained on 1024- or 2048-channel analyzers with punched-tape output. Data reduction of the spectra and the various calculations were done by standard computer techniques.

The resonant level energies, total radiation widths, and ground-state partial widths are shown in Table I. The decay schemes of the 8998- and 7696-keV resonant levels in ^{120}Sn, the 7820-keV level in ^{86}Sr, the 7696-keV level in ^{66}Zn, and the 7820-keV level in ^{80}Se are shown in Figs. 1–4.

III. REDUCED TRANSITION WIDTHS

Following Batholomew's notation[23] we define a reduced partial width for $E1$ and $M1$ transitions by

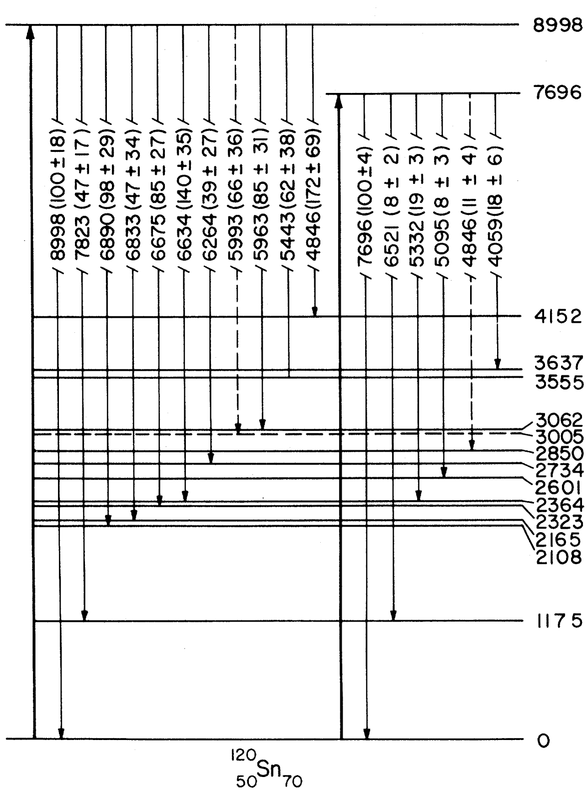

FIG. 1. Decay scheme of ^{120}Sn obtained in this work through photonuclear excitation.

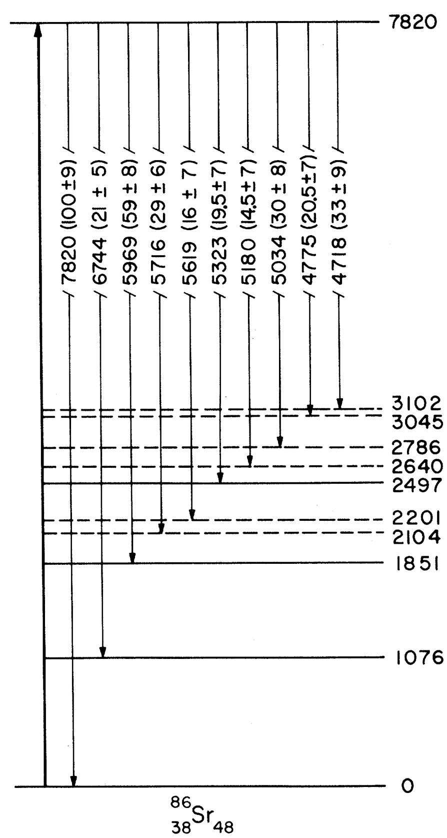

FIG. 2. Decay scheme of ^{86}Sr obtained in this work through photonuclear excitation.

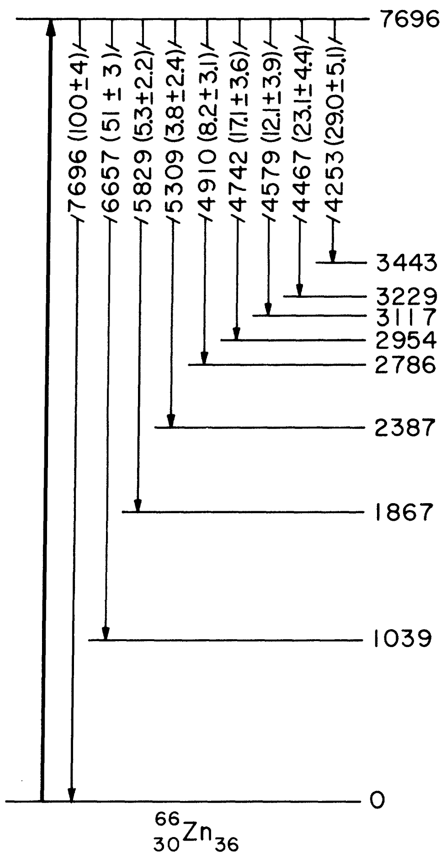

FIG. 3. Decay scheme of ^{66}Zn obtained in this work through photonuclear excitation.

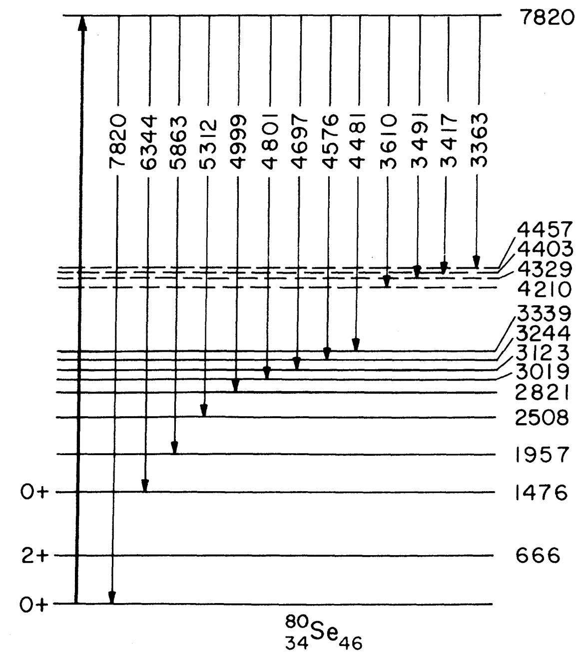

FIG. 4. Decay scheme of ^{80}Se obtained in this work through photonuclear excitation.

the following expressions:

$$K_{E1} = \frac{\Gamma_{obs}(E1)\ (\mathrm{eV})}{E^3 A^{2/3} D\ (\mathrm{MeV}^4)}, \tag{1a}$$

$$K_{M1} = \frac{\Gamma_{obs}(M1)\ (\mathrm{eV})}{E^3 D\ \ (\mathrm{MeV}^4)}, \tag{1b}$$

where Γ_{obs} is the observed transition width in eV, E the energy of the transition in MeV, and D the level spacing in the neighborhood of the resonant level, also in MeV. A compilation of known $E1$ and $M1$ high-energy primary transitions following neutron capture is given in the above-mentioned review article,[23] in Carpenter's report,[24] and in a recent report of Bollinger.[25] From the systematics of these results a rough criterion can be obtained as to the electric or magnetic character of dipole transitions; transitions having $K_{E1} \gtrsim 2\times 10^{-3}$ (or $K_{M1} \gtrsim 50\times 10^{-3}$) may be regarded as $E1$, while those having $K_{M1} \lesssim 10^{-3}$ are very likely to be of magnetic dipole character.

This criterion can be adapted to the present results, provided that the level spacing D is known. Recent compilations of level spacings obtained in the neutron-resonance region were published in an article by Oliva and Prosperi[26] and in a recent book by Lynn.[27] However, due to the fact that the nuclei studied by the (γ, γ') reactions are all stable while the product nuclei obtained in the resonance-neutron-capture reaction are in many cases unstable, there is a lack of experimental information on the values of the level spacings in nuclei considered in this work. For this reason we calculated the reduced widths in a consistent way using theoretical values of D given by Cameron's[28] level-density formula. The relevant values of D, K_{M1} and K_{E1} are shown in Table I. Where experimental values of D (at the neutron binding energy) are known, they were corrected for the energy dependence using Le Couteur's formula[29] based on the Fermi-gas model of the nucleus and are shown in Table I in parenthesis. As one can see, those latter values are generally in satisfactory agreement with the calculated ones.

IV. GIANT-DIPOLE-RESONANCE EXTRAPOLATION

The single-level absorption cross section of a photon having an energy E may be written as

$$\sigma_a = \frac{\lambda^2}{2\pi} g \frac{\Gamma_0}{\Gamma} \frac{1}{[(2/\Gamma)(E-E_0)]^2+1}, \tag{2}$$

where $\lambda = hc/E$ is the photon wavelength, g is the statistical factor $(2I_0+1)/(2I_g+1)$, I_0 and I_g being the spins of the excited level and that of the ground state, respectively, Γ_0 is the partial width for the transition to the ground state, and Γ is the total width.

Averaging this expression over a large number of levels in an energy interval ΔE gives

$$\langle\sigma_a\rangle = (\pi\hbar c/E)^2 g\langle\Gamma_0\rangle/D\,, \quad (3)$$

where D is the average level spacing of the n levels in the interval ΔE and $\langle\Gamma_0\rangle$ is the average ground-state partial width in the given energy interval. Thus the "strength function" $\langle\Gamma_0\rangle/D$ may be written as

$$\frac{\langle\Gamma_0\rangle}{D} = \frac{1}{g}\left(\frac{E}{\pi\hbar c}\right)^2\langle\sigma_a\rangle\,, \quad (4)$$

this expression still being correct when appropriate account is taken for the thermal Doppler broadening of the excited levels.

If we consider only electric dipole absorption, then according to Axel,[19] this part of $\langle\sigma_a\rangle$ may be obtained by extrapolation of the giant-dipole absorption cross section given by

$$\langle\sigma_a\rangle = \frac{0.013A}{\Gamma_g}\,\frac{E^2\Gamma_g^{\,2}}{(E_g^{\,2}-E^2)^2+E^2\Gamma_g^{\,2}}\ \mathrm{b}\,, \quad (5)$$

where A is the mass number, Γ_g the giant-resonance half width, and E_g its peak energy. The normalization factor $0.013A/\Gamma_g$ takes care of the sum-rule requirement.[30] Combining the last two expressions one obtains

$$\frac{\langle\Gamma_0\rangle}{D} = 3.4\times10^{-6}\frac{A}{g}\,\frac{E^4\Gamma_g}{(E_g^{\,2}-E^2)^2+E^2\Gamma_g^{\,2}}\,. \quad (6)$$

Axel approximates this formula in the 7-MeV region to

$$\frac{\langle\Gamma_0\rangle}{D} = C\left(\frac{E}{7}\right)^5\left(\frac{A}{100}\right)^{8/3}\left(\frac{\Gamma_g}{5}\right)\left(\frac{3}{g}\right), \quad (7)$$

with $C = 2.2\times10^{-5}$.

Table I summarizes the values of the numerical constant C calculated according to this formula, using the experimental values of Γ_0 in place of $\langle\Gamma_0\rangle$, and the calculated values of D, listed in columns 5 and 6, respectively, of the table.

V. FLUCTUATIONS OF PARTIAL RADIATIVE WIDTHS

Resonance levels obtained via the (γ,γ') reaction deexcite predominantly via dipole transitions, and hence the fluctuations in partial-transition intensities permit a direct comparison with those of the neutron resonances. Since, however, only one or two (γ,γ') resonance levels per nucleus have been found in most of the nuclei studied, it was not possible to analyze the distribution for individual nuclei, and we therefore consider here transitions found in the group of even-even nuclei having low-lying 2^+ and 0^+ vibrational levels. Table II shows the relative transition strengths to the ground state and to the one- and two-phonon levels for 14 (γ,γ') resonance levels. The intensities in each case are normalized to 100 for the ground-state transition. It can be seen that the average ground-state transition intensity is some three times as strong as the average of the transitions to each of the higher-lying levels, which are approximately equal. This is in contradiction to the corresponding results for the neutron resonances, where, after applying a correction for the energy dependence of the transition widths, either in the form of an E^3 dependence or an E^5 dependence,[19] all three transition strengths show essentially the same average value.

The difference between the two experiments can be explained by the fact that the (γ,γ') excitation cross section is proportional to the ground-state

TABLE II. Relative transition intensities to ground state and first two 2^+ states from (γ,γ') resonance levels.

Nucleus	Resonant level energy (MeV)	First 2^+ level (MeV)	Second 2^+ level (MeV)	Relative intensity Ground state	First 2^+	Second 2^+	Ratio r	Reference
^{142}Ce	5.669	0.639	1.540	100	4.6 ± 3.0	<5	>1.1	b
^{130}Te	7.637	0.840	1.588	100	16.5	15.0	1.1	b
^{130}Te	7.538	0.840	1.588	100	113 ± 10	125 ± 25	1.38	5
^{128}Te	7.730	0.743	1.521	100	< 3	106 ± 5	>35.0	b
^{126}Te	7.813	0.667	1.414	100	< 30	160 ± 70	>5.3	b
^{118}Sn	6.998	1.230	2.040	100	26 ± 2	<0.6	>45.0	b
^{112}Cd	7.632	0.617	1.310	100	18.5 ± 3	1.9 ± 0.4	10.0	11
^{110}Cd	6.500	0.658	1.476	100	18.2 ± 1.3	1.7 ± 1.5	10.6	b
^{100}Mo	7.646	0.537	1.065	100	65 ± 2	7 ± 2	9.3	b
^{86}Sr	7.820	1.076	1.851	100	21 ± 5	59 ± 8	2.8	b
^{80}Se	7.820	0.666	1.476 (0+)	100	≤1	18.5 ± 3	>18.5	b
^{66}Zn	7.696	1.039	1.867	100	51.0 ± 3.0	5.3 ± 2.2	10.1	b
^{66}Zn	7.368	1.039	1.867	100	~0.3	14.3 ± 0.7 [a]	47.7	17
^{62}Ni	7.646	1.172	2.303	100	8.6 ± 2.2	2.9 ± 2.0	3.0	11

[a] Estimated error.

[b] Present work.

transition width Γ_0,[3] and hence there is a strong experimental bias towards detecting those resonances having much larger than average values of the branching ratio Γ_0/Γ. The distribution of the observed intensities for transitions to the ground state is hence very far from the true distribution and it was decided to include in the analysis only transitions from the resonance state to the first two 2^+ states.

According to Porter and Thomas[22] the distribution of partial reaction widths is given by a χ^2-type distribution of the form

$$P(x, \nu)dx = [\Gamma(\nu/2)]^{-1}(\nu x/2)^{(\nu/2)-1}e^{-\nu x/2}dx\,, \qquad (8)$$

where x is the ratio of partial to average radiation widths and ν is the number of degrees of freedom. For a reaction proceeding via one open channel it is expected that $\nu = 1$.

If we assume that the fluctuations in the partial radiation widths are described by a χ^2 distribution with the same number of degrees of freedom for each of these nuclei, then the fluctuations in the ratio r of intensities to the first two vibrational levels can be used to determine the distribution law. The integral distribution of r is shown in Fig. 5(a) for the 14 (γ, γ') resonance levels of Table II. Symmetry properties of the derived distribution permit choosing r to be always greater than one, e.g., to be the ratio of the stronger intensity transition to that of the weaker transition.

Since r is a ratio of intensities, no additional intercalibration is required in studying the distribution. This is to be compared with the intercalibration procedure required in comparing intensities from the different neutron-resonance levels, this being based on the assumption of an essentially constant total radiation width for each level.

For comparison, the corresponding distribution of r for 20 of the ^{196}Pt neutron resonance levels calculated from the data of Samour *et al.*[31] is shown in Fig. 5(b). No correction for the energy dependence of the transition intensities was applied, since the derived distributions are not sensitive to this correction. It can be seen that the general features of the distribution of r in Figs. 5(a) and 5(b) are quite similar.

The probability distribution of the ratio r' of two uncorrelated variates having the same χ^2 distribution follows a Fisher z distribution,[32] and the integral form of this distribution, defined as the probability of a ratio greater than r', is given by

$$P(r', \nu) = B_{1+r'}(\nu/2, \nu/2)/B_\infty(\nu/2, \nu/2)\,, \qquad (9)$$

where $B_{1+r'}(\nu/2, \nu/2)$ is the incomplete beta function defined by

$$\int_0^{1/(1+r')} (1-x)^{(\nu/2)-1}x^{(\nu/2)-1}dx\,, \qquad (10)$$

and $B_\infty(\nu/2, \nu/2)$ is the complete beta function equal to $[\Gamma(\nu/2)]^2/\Gamma(\nu)$.

The probability of a ratio greater than r' can be shown to be equal to the probability of a ratio less than $1/r'$, permitting the experimental ratio r to be chosen always greater than 1. The corresponding distribution function is obtained by multiplying the probability distribution given by Eq. (9) by a factor of 2. The expected distributions, corresponding to values of $\nu = 0.6$, 1, and 2 are shown in Fig. 5. It can be seen that both sets of data are compatible with values of ν between 1 and 2. Since many of the observed values of r are lower estimates, the true fit will lie towards a lower value of ν, i.e., closer to 1. The "maximum-likelihood" procedure was applied for calculating ν by maximizing the logarithm of the maximum-likelihood function $L(\nu)$ given by

$$L(\nu) = \prod_{i=1}^{N} \rho(r_i, \nu)\,, \qquad (11)$$

and where $\rho(r, \nu)$ is the derivative of $P(r, \nu)$ with respect to r, and N is the number of experimental results.

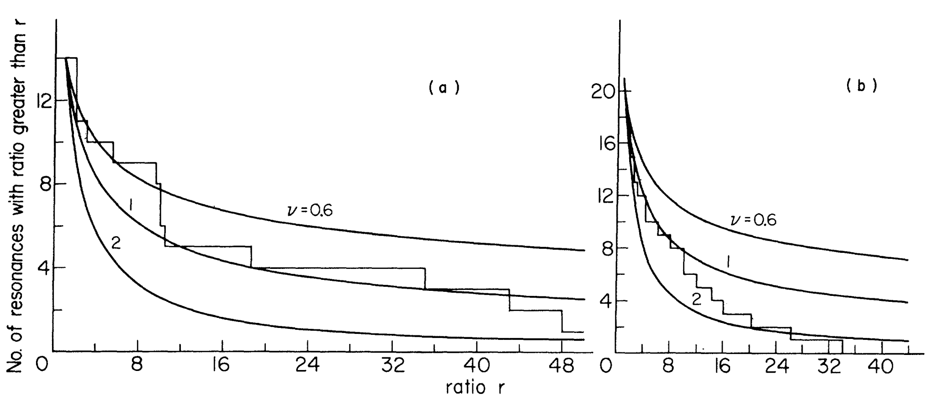

FIG. 5. Integral distribution of the ratios of transition intensities to the two lowest excited states. (a) For 14 resonant levels obtained in (γ, γ') experiments, (b) for 20 neutron resonance levels in ^{196}Pt (Ref. 31).

This leads to the following result

$$\frac{1}{N}\sum_{i=1}^{N}\ln\frac{(1+r_i)^2}{r_i}=\psi(\nu_m)-2\psi\left(\frac{\nu_m}{2}\right), \qquad (12)$$

$\psi(\nu)$ being the logarithmic derivative of the γ function $\Gamma(\nu)$. Using the tables of an earlier work,[33] a value of $\nu_m = 1.4$ was obtained, in good agreement with the expected value of 1. However, this procedure does not take into account the experimental errors involved, which were included by modifying the maximum-likelihood function to include the range of experimental errors, and a new value of $\nu_m' = 1.04$ was obtained. In order to find the probability of obtaining the above value from populations having different degrees of freedom, a Monte Carlo calculation was performed, using the same definition of ν_m' and taking into account the actual experimental conditions and uncertainties.

The calculated probability distributions for ν_m for values of $\nu_0 = 1$ and $\nu_0 = 2$ are shown in Fig. 6. This gives a probability of about 35% obtaining a value of ν_m as small as 1.04 for $\nu_0 = 1$, and about 6% for the case $\nu_0 = 2$. Although from statistical considerations this does not provide an unambiguous determination of ν_0, it does, however, indicate that the presently accumulated data for the (γ, γ') resonant levels are fully compatible with the Porter-Thomas distribution.

DISCUSSION

The total radiation widths of the resonance levels excited by the (γ, γ') reaction lie in the range 20 meV to 5 eV (as can be seen from Table I). It is interesting to compare this with the corresponding average values obtained from thermal- and resonance-neutron-capture data,[27] which are in a similar energy range, namely 30–600 meV. Although the spread of values in Table I seems to be somewhat wider than for the neutron data, it should be remembered that the former are radiation widths of single levels, whereas the latter are usually averaged over many levels. A direct comparison of total radiation widths measured for the same nuclei for these two reactions is only possible for two nuclei, namely, ^{139}La and ^{112}Cd, since the nuclei studied with the (γ, γ') reaction could not normally be reached in neutron-capture γ reactions and vice versa. For ^{139}La the average total radiation width in neutron-capture studies is 99 ± 6 meV at the neutron binding energy 8.78 MeV, compared with an average of 56 ± 17 meV at 6.5 MeV for the three γ resonances. The corresponding values for ^{112}Cd were 120 ± 20 meV at 9.48 MeV (neutron threshold) and 130 meV at the single γ resonance energy of 7.632 MeV. The total radiation width is not expected to be very strongly dependent on the excitation energy. Using Cameron's formula,[28]

$$\overline{\Gamma}_\gamma = A^{2/3}\overline{D}_0(U)\int_0^U \frac{E^3}{\overline{D}_0(U-E)}dE\,,$$

one finds the width for the (γ, γ') resonance to be some 65% of that at the neutron binding energy for both the above nuclei. This is in good agreement with the results obtained for ^{139}La. In the case of ^{112}Cd, new results (see Ref. h, Table I) are lower than the value quoted above, and will thus give better agreement with the Cameron formula.

While the total radiation widths show a very similar behavior in these two reactions, there are striking differences in the observed ground-state transition widths. The ground-state branching ratio has an average value of about 50% for the levels shown in Table I. This is much larger than the corresponding results from neutron-capture data, where corresponding branching ratios of 1% and less are typical. This is a well-known feature of the γ-resonance technique, which favors levels having large values of the ratio Γ_0/Γ and of Γ_0, and having values of spin permitting dipole excitations from the ground state. On the other hand, some 40% of the neutron-capture results refer to radiation widths in odd-odd nuclei having a very high density of low-lying states, which reduce the ground-state branching ratio. In addition, electric dipole deexcitation to the ground state is not always possible for neutron-capture states. The values of K_{E1} and K_{M1} given in Table I show that the excitation mechanism is predominantly $E1$, in agreement with the conclusions of Axel.[19]

As mentioned above, the experimental technique for the (γ, γ') method introduces an inherent cutoff for smaller values of Γ_0. Hence one may expect that the factor C, defined by Eq. (7), would be higher than the predicted 2.2×10^{-5} given by Axel, as can be actually seen in Table I.

The large differences observed in the intensities

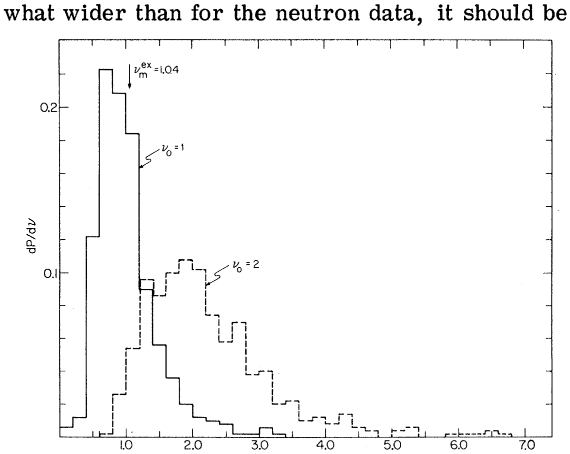

FIG. 6. Probability distributions for the maximum-liklihood value of v_m derived from the Monte Carlo calculations using values of $v_0 = 1$ and $v_0 = 2$.

of transitions to the lower levels may be an indication of nuclear-structure effects in the transition matrix elements between the resonance level and low-lying levels. Estes and Min[34] have pointed out for both the 7.632-MeV resonances in ^{112}Cd and in ^{62}Ni, that whereas in both cases the first-phonon 2^+ state is populated from the resonant state, among the two-phonon states only the 0^+ is populated while the 2^+ is populated either to a very small extent or not at all. They attributed this effect to very different components of wave functions of the 0^+ and 2^+ members of the two-phonon triplet for both nuclei. Shikazono and Kawarasaki[17] noticed a similar effect in the 7.368-MeV level of ^{66}Zn, where in this case the 2^+ member of the two-phonon triplet was preferentially populated compared with the 0^+, which they attributed to differences in the character of these two states.

However, the observed fluctuations in the ratios of the partial radiation widths to the one- and two-phonon states of the 14 nuclei summarized in Table I have been shown for these nuclei to be fully compatible with a Porter-Thomas distribution of partial radiation widths. The present analysis of the fluctuations of widths based on the ratio of intensities to different levels is strongly dependent on the assumption that radiative transitions to these levels are completely uncorrelated. Such a correlation could be present if that part of the wave function of the low-lying state which appears in the transition matrix elements was identical for both low-lying levels, or different only by a constant factor.[22] Since a positive correlation has been found between radiative and neutron partial widths of unbound resonant levels,[35] the possibility of correlation in the partial radiative widths must be carefully examined. Bollinger *et al.*[36] studied this problem with neutron resonances in ^{195}Pt, ^{183}W, and ^{77}Se, and Wasson *et al.*[37] with neutron resonances in ^{182}Ta, and both groups found no evidence for correlation between the partial radiation widths. A similar analysis by the present authors using more-recent data on ^{196}Pt published by Samour *et al.*[31] confirmed this result. This provides a reasonable basis for the assumption of no correlation in the present analysis. Should the observed distribution in the ratio of partial radiation widths have been caused not by random fluctuations, but by a distribution of different correlations among the different nuclei, then it would be difficult to explain why the result so closely follows the theoretical curve for the Porter-Thomas distribution.

However the conclusions of the fluctuation properties of these partial radiative widths can only be regarded as an average property for these nuclei. While the earlier studies on neutron-resonance levels[36,37] confirmed the Porter-Thomas distribution for many nuclei, recently a number of deviations have been observed in neutron resonances in ^{238}U, ^{182,186}W, ^{169}Tm, and ^{103}Rh corresponding to narrower distributions with more than one degree of freedom.[38] These deviations have been explained by Beer[39] in terms of a model with two different groups of compound states. For the present data on the γ-resonant levels it is, of course, not possible to exclude the possibility that one or two of these nuclei may in fact have distributions considerably narrower than the Porter-Thomas. However, increased data on new γ resonances in these nuclei will permit a more quantitative analysis for each nucleus.

The present results show that the γ-resonance technique can be usefully applied in the bound region up to a few MeV below the particle threshold, and hence considerably extends the available region for studying the properties of radiation widths.

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Nuclear-Resonance Fluorescence in Xe^{130}†

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The 536-keV (2^+) first excited state of Xe^{130} has been investigated by means of nuclear-resonance-fluorescence scattering experiments. The use of a Ge(Li) detector allowed a good determination of the Rayleigh scattering contribution which amounted to about 30% of the resonant peak. The level width was found to be $(5.2 \pm 0.9) \times 10^{-5}$ eV, corresponding to a mean life of $(1.3 \pm 0.3) \times 10^{-11}$ sec and a $B(E2)\uparrow$ of $(0.69 \pm 0.15)e^2 \times 10^{-48}$ cm^4. From this result and the relative transition probabilities determined previously in a Coulomb-excitation experiment by Pieper, Anderson, and Heydenburg, the absolute $B(E2)$ values for the first excited states of Xe^{128} and Xe^{132} were obtained.

INTRODUCTION

The lifetimes of many of the first excited states of the even-even nuclei in the $Z = 50$ region of the Periodic Table are much shorter than the corresponding single-particle estimates and indicate a collective kind of behavior similar to that occurring in the deformed rare-earth nuclei. There has been continuing interest[1-3] in the investigation of possible equilibrium deformations in this region. Relative reduced transition probabilities for the first excited states of Xe^{128}, Xe^{130}, and Xe^{132} have been obtained by means of Coulomb excitation[4,5] and a value of $B(E2)\uparrow = 0.48e^2 \times 10^{-48}$ cm^4 was assigned to the 536-keV level of Xe^{130} (quoted by Hamilton[6]) on the basis of a comparison with similar states in neighboring even-even nuclei. An absolute determination of $B(E2)$ for one of the above isotopes would enable an accurate assignment of values for the other two isotopes. Considering the above, we undertook to measure the lifetime of the 536-keV level in Xe^{130} by means of nuclear-resonance-fluorescence (NRF) scattering.[7]

The present study used the β decay of 12.4-h I^{130}