PHYSICAL REVIEW C VOLUME 23, NUMBER 4 APRIL 1981

Dipole radiative strength functions from resonance neutron capture

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(Received 22 October 1980)

Photon strength functions have been derived from discrete neutron resonance data for electric and magnetic dipole radiation using the methods of slow neutron time-of-flight spectroscopy. The data cluster reasonably well around strengths of $b(E1) \cong 0.04$ Weisskopf units/MeV and $b(M1) = 1.4$ Weisskopf units/MeV, respectively.

[NUCLEAR REACTIONS Measured $\Gamma_{\gamma if}$, J, π, $\sigma(n,\gamma)$; derived $\langle \Gamma_{\gamma if} \rangle$, $\Gamma/D(E1)$, $\Gamma/D(M1)$.]

I. INTRODUCTION

There has been considerable interest in the distribution of radiative strength in nuclei ever since the discovery of the giant dipole resonance. Using photons as nuclear probes, thereby exploiting the precise knowledge of the electromagnetic interaction, the general features of photoexcitation have been charted systematically with nuclear size and shape.[1] Further information on multipoles, other than the electric dipole, has come more recently from electron scattering[2] and, to a lesser extent, from hadronic probes.[3]

In the region of excitation corresponding to the neutron separation energy, the radiative strength may be uniquely determined by direct determination of the parameters of the fine structure states (neutron resonances). At these excitations, the nuclear states are well separated and, very near particle threshold, may decay predominantly by emission of radiation. The average properties of these states determine a photon strength function which is related to the photoabsorption cross section. This cross section is, for the dominant electric dipole decay, just the low energy tail of the giant resonance observed in the nuclear photoeffect.

For neutron capture reactions in this particle (neutron) threshold region, there is available a technique for the unequivocal measurement of the parameters of the fine structure resonances. This is the method of slow neutron time-of-flight spectroscopy. The absolute measurement of resonance parameters, including specifically the partial radiative widths to discrete final states of the residual nucleus, allows a determination of the photon strength function in absolute units. This method was used originally by Carpenter.[4] Other methods, such as spectrum fitting as described by Bartholomew *et al.*[5] with low resolution sodium iodide detectors, involve assumptions about the quantum numbers and other parameters of the capture state in order to extract photon strengths. Thus the slow neutron techniques allow us to provide absolute calibration points for other techniques in the narrow region near threshold.

Moreover, this threshold region provides a severe test for the assumption that the giant resonance is describable in terms of a given function—such as the Lorentzian—in a region several half widths removed from the resonance peak. It is for these reasons that the present study was undertaken.

In the past, only a number of limited surveys[4-9] have been made of the radiative electric or magnetic dipole strength behavior as a function of mass and energy. Most of the data in these surveys have been obtained from the (γ,n) reaction, the (γ,γ') reaction, and from resonance-averaged and discrete-resonance neutron capture. Both the (γ,n) and the (γ,γ') reactions at low excitation energies have the disadvantage that they are characterized by a small number of transitions and therefore do not reflect an average behavior. Thermal and resonance-averaged neutron capture gamma rays result from the decay of a generally complicated set of initial states which is formed by the superposition of several states of differing spins and sometimes differing parities. Resonance averaged spectra have been used to determine both photon and neutron cross sections, since the average capture cross section is proportional to the product of $\langle\Gamma_n\rangle$ and $\langle\Gamma_\gamma\rangle$. Discrete-resonance capture at low excitation energies, however, occurs in well-defined capture states whose spins, parities, and resonance parameters, e.g., total radiation widths, are usually known. Often there are several resonances available, each with a sizable number of transitions. Absolute partial radiative widths can be determined from the branching ratios of primary transitions and a knowledge of the total radiative width of the capture state. It should be obvious, then, that descrete-resonance neutron capture can provide the most reliable parameters for the calculation of radiative strength functions.

The present paper reports a comprehensive survey of all known $E1$ and $M1$ absolute partial widths resulting from discrete-resonance capture in approximately 50 nuclides. Where necessary, some of the previously published data have been renormalized to take advantage of improved knowledge of the resonance parameters and neutron cross sections. An effort has been made to choose a convenient normalization standard in order to reduce the likelihood of differing systematic uncertainties. The resulting survey provides an internally consistent and accurate basis for testing models for the distribution of radiative strength in nuclei.

II. THEORETICAL DISCUSSION

Unfortunately there is no single universally accepted definition of the radiative strength function. There exists a variety of expressions which have been defined for the sake of convenience and to test specific theoretical models. We will present only a limited discussion of the photon strength function definitions for electric and magnetic dipole transitions that are in common use.

A. Electric dipoles

Historically, the single-particle strength function has had many related expressions. An excellent overview of these expressions and their relations has been given by Lone.[10] An expression commonly used[5] by neutron physics specialists is

$$k(E1)=\langle\Gamma_{\gamma if}(\text{eV})\rangle D^{-1}(\text{eV})E_\gamma^{-3}(\text{MeV}^3)A^{-2/3}\,, \qquad (1)$$

where $\langle\Gamma_{\gamma if}\rangle$ is the average partial width for a transition from an initial state i to a final state f, D is the average resonance spacing for resonances with the same spin parity as i, E_γ is the transition energy, and A is the nuclear mass. As pointed out by Lone[10] and Axel,[11] it is more revealing to express k in Weisskopf units (W.u.) per MeV, that is, in terms of the single particle strength:

$$b(E1)=\frac{B(E1)\text{per MeV}}{B_W(E1)}=1.48\times10^7 k(E1). \qquad (2)$$

In these terms, the k_{E1} value estimated by Bartholomew from thermal neutron capture, 3×10^{-9} MeV^{-3}, corresponds to about 0.05 W.u./MeV.

Axel[12] has pointed out that in the region of excitation corresponding to the neutron binding energy the absorption of radiation occurs via fine structure resonances. The average absorption cross section of these resonances, which is related to the photon strength function, is given by

$$\langle\sigma_a\rangle=2\pi^2\lambda\!\!\!^{-2}g_j(\Gamma_{\gamma0}/D)\,, \qquad (3)$$

where $\Gamma_{\gamma0}$ represents the width for the transition from the ground state. Presumably the secular energy variation of $\langle\sigma_a\rangle$ is describable by the tail of the giant resonance. Two forms have typically been used to describe the giant resonance: (a) a Lorentzian form

$$\sigma_a=\sigma_0\left\{\frac{\Gamma(E_0)}{\Gamma(E)}\left[\frac{(E_0{}^2-E^2)^2}{E^2\Gamma^2(E)}+1\right]^{-1}\right\} \qquad (4)$$

and (b) a Breit-Wigner form

$$\sigma_a=\sigma_0\left\{\frac{\Gamma(E_0)}{\Gamma(E)}\left[\frac{4(E_0-E)^2}{\Gamma^2(E)}+1\right]^{-1}\right\}, \qquad (5)$$

for a resonance with a peak cross section σ_0 and a width Γ. Forms (a) and (b) have been written in such a way as to emphasize the fact that the width Γ, which describes the damping of the giant resonance into the fine structure states, will in general vary with energy. For example, Arenhovel, Greiner, and Danos,[13] and also Dover, Lemmer, and Hahne,[14] suggest that Γ varies as E^2.

When considering the (n,γ) or inverse reaction, the above expression refers specifically to the ground state transition $\Gamma_{\gamma0}$. It is conventional to use the Brink[15] hypothesis and apply the identical relation to any transition proceeding from the capture state λ to any final state f of the final nucleus. This hypothesis is equivalent to the assumption that an analogous giant resonance is built upon each excited state of the final nucleus. The individual partial radiative widths are related to the absorption cross section by

$$\langle\Gamma_{\gamma if}(\text{eV})\rangle=8.67\times10^{-8}D(\text{eV})E_\gamma^2(\text{MeV})\sigma(\text{mb}), \qquad (6)$$

where D is the spacing of levels of appropriate spin-parity, E_γ is the γ-ray energy, and σ the absorption cross section.

Axel[12] developed an approximate relationship from Eqs. (4) and (6) valid for a wide range of nuclides by assuming a constant giant resonance width Γ of 5 MeV, an energy of 80 $A^{-1/3}$ MeV, and a peak cross section of 13 A/Γ mb. Axel defines a strength function S as follows:

$$S=\langle\Gamma_{\gamma if}\rangle D^{-1}E_\gamma^{-5}A^{-8/3}. \qquad (7)$$

As we shall see, this expression provides a significantly better global fit to the strength function, and confirms the oft-observed empirical fact that the primary capture γ rays display a harder spectrum than suggested by the E^3 dependence of the single particle model.

B. Magnetic dipoles

Bartholomew suggests an analogous quantity to k_{E1} for the magnetic dipole case.

$$k_{M1}=\langle\Gamma_{\gamma if}(\text{eV})\rangle/D(\text{eV})E_\gamma^3(\text{MeV}^3), \qquad (8)$$

and similarly to (2) we can define

$$b(M1) = \frac{\langle B(M1)\text{ per MeV}\rangle}{B_W(M1)}\,,$$
$$= 4.82 \times 10^7 k_{M1}\,. \qquad (9)$$

Thus the value of $k_{M1} = 4 \times 10^{-9}$ MeV^{-3}, suggested by Bartholomew[5] as characteristic of thermal neutron capture, translates to a value of about 0.2 W.u./MeV. However, the early review by Bartholomew[5] was based on a limited data set. More recent work led Bollinger[7] to suggest a value of $b_{M1} \approx 1$ W.u./MeV. The contrast between $b(E1) \approx 0.05$ and $b(M1) \approx 1$ indicates the transfer of $E1$ strength to the giant resonance region on the one hand and on the other the possible influence of collective $M1$ strength situated somewhere near the neutron binding energy. It is one of the purposes of the present study to give more accurate values for both $E1$ and $M1$ strengths.

There exists considerable experimental evidence[16-18] which suggests the presence of an $M1$ giant resonance located near the neutron separation energy. It has been postulated[19] that this enhancement results from spin-flip transitions from states of $j = l + \frac{1}{2}$ to $j = l - \frac{1}{2}$ with an energy corresponding to the spin-orbit splitting. In a very simple picture, a collective $M1$ giant resonance can be thought of as a combination of both proton and neutron spin-flip excitations. If the wave functions for the isovector and isoscalar components are written as

$$|1^+\rangle_v = a|p^{-1}p\rangle - b|n^{-1}n\rangle$$

and

$$|1^+\rangle_s = a|p^{-1}p\rangle + b|n^{-1}n\rangle\,,$$

the reduced transition probability is given by[13]

$$B(M1;\, 1^+ \to 0^+) = \frac{\mu_0^{\,2}}{2\pi}\left\{(g_{sp} - g_{lp})\left[\frac{l_p(l_p+1)}{2l_p+1}\right]^{1/2} a + (g_{sn} - g_{ln})\left[\frac{l_n(l_n+1)}{2l_n+1}\right]^{1/2} b\right\}^2. \qquad (10)$$

Here, l is the angular momentum of the shell, g is the spin or orbital g factor, and μ_0 is the nuclear magneton. This expression clearly indicates that the $M1$ transition probability increases with l and therefore one would expect heavy nuclei near closed shells to show the strongest $M1$ excitations. Unfortunately, the dependence of the $M1$ transition probabilities on the nuclear structure has made it impossible to develop a simple global expression for the $M1$ strength function as was done in the case of $E1$ transitions.

III. EXPERIMENTAL DETAILS

The fast chopper time-of-flight facility[20] at the Brookhaven HFBR was used to determine many of the absolute partial widths contained in the survey. One of the following three methods was used to obtaine the partial widths: (1) an absolute measurement was performed, (2) a normalization relative to the ^{197}Au 4.9 eV resonance was made, or (3) a normalization relative to the thermal intensities of ^{197}Au was used. Methods (2) and (3) rely on knowing the partial widths of ^{197}Au at 4.9 eV and the intensities at thermal. These have been accurately determined and are available.[21] The resonance parameters[22] are also well known and ^{197}Au has a high capture cross section at these energies, thus allowing for rapid data accumulation. These advantages make ^{197}Au a useful and convenient normalization standard and it has been used for most of the nuclides in our survey.

The observed count rate for a given transition $i \to f$ may be written

$$A_{\gamma if} = \epsilon(E_\gamma) N_i \Gamma_{\gamma if}/\Gamma_{\gamma iT}\,, \qquad (11)$$

where $\epsilon(E_\gamma)$ is the detection efficiency at E_γ for a particular geometry, N_i represents the neutron capture rate in the resonance i, and $\Gamma_{\gamma if}$, $\Gamma_{\gamma iT}$ are the partial and total radiative widths, respectively. N_i is in general a complicated function of neutron energy. It includes the effect of target thickness, multiple scattering, Doppler broadening, and the resonance wing contributions. These corrections are typically small, usually 5–10% in magnitude, and are readily made using standard techniques of neutron resonance parameter analysis.

In methods (2) and (3) a comparison of the transition intensities of the standard Au foil and the nuclide in question was performed by using a composite target. The partial widths for the samples may be written as

$$\Gamma^s_{\gamma if} = \left(\frac{A^s_{\gamma if}}{A^{Au}_{\gamma if}}\right)\left(\frac{\epsilon^{Au}}{\epsilon^s}\right)\left(\frac{N^{Au}_i}{N^s_i}\right)\left(\frac{\Gamma^{Au}_{\gamma if}}{\Gamma_{\gamma iT}}\right)\Gamma^s_{\gamma iT}\,. \qquad (12)$$

Once the values of $\Gamma^s_{\gamma if}$ have been determined for a given resonance i by any of the three methods, they may be used to calibrate all resonances j for a sample s by assuming that

$$\frac{A^s_{\gamma if}}{A^s_{\gamma jf}} = \left(\frac{N^s_i}{N^s_j}\right)\left(\frac{\Gamma^s_{\gamma if}}{\Gamma^s_{\gamma jf}}\right)\,. \qquad (13)$$

It is reasonable to assume that the number of captures is proportional to the sum of a number of observed secondary transitions in a given resonance.

For a number of nuclides in the literature absolute partial widths were not published. For these nuclides a normalization experiment as described above was performed, and the published relative intensities were renormalized. The absolute partial widths for the five cases so treated are given in Table I. A 20% normalization uncertainty has been adopted and was based on the typical uncertainties in the values of the total radiative width Γ_γ and of the resonance level spacing D.

IV. THE SURVEY AND RESULTS

A comprehensive survey of all known $E1$ and $M1$ absolute partial widths from the (n,γ), (γ,n), and (γ,γ') reactions has been made for ~50 nuclides. It should be noted that the (γ,γ') results were characterized by a limited number of transitions and large Porter-Thomas fluctuations[23] and therefore were not included in the calculations. The following criteria were used in establishing this survey:

(1) Only discrete-resonance data were used in order to take advantage of the well-defined capture states of known spins and parities.

(2) Only primary transitions known to be either electric or magnetic dipoles were used.

(3) Thermal data were included only if a bound state of known spin and parity dominated the thermal capture cross section.

(4) The most recent reported measurement for a nuclide was used.

(5) Where necessary, previous data were renormalized to take advantage of improved knowledge of the resonance parameters and cross sections.

(6) Data for resonances of differing spin and parity in the same nuclides were treated separately to account for the spin dependence of the level spacing.

(7) A 20% normalization uncertainty was adopted, except where an estimate was given, and was based on the typical uncertainties of the resonance parameters.

(8) The statistical, normalization, and Porter-Thomas uncertainties were added in quadrature to form the total uncertainty for each nuclide which was usually dominated by the Porter-Thomas term.

(9) A chi-square test was used to compare the result for the different theoretical formalisms.

TABLE I. Absolute normalizations for selected nuclides. E_n refers to neutron resonance energy, E_γ to the primary γ-ray energy, and $\Gamma_{\gamma if}$ to the partial radiative width corresponding to E.

Final nucleus	E_n (eV)	E_γ (keV)	$\Gamma_{\gamma if}$ (meV)
^{57}Fe	1167	7646	110 ± 5
^{106}Pd	11.8	7631	0.44 ± 0.03
^{128}I	20.5	6682	1.24 ± 0.12
^{144}Nd	55	5522	1.42 ± 0.14
^{176}Lu	(Thermal)	5826	0.063 ± 0.015

A complete listing of the surveyed partial widths and the resonance parameters may be obtained on request from the authors. Table II contains a description of the data base and literature references.

A. Electric dipole strength function

The $E1$ strength function behavior was investigated using the single-particle model, Axel's approximation, and the Lorentz approximation formalisms.

The single-particle expression as given by Eq. (1) was used to calculate the $b(E1)$ value for all of the surveyed $E1$ transitions. An average value for $b(E1)$ of 0.043 ± 0.004 W.u./MeV $[k_{E1} = (2.9 \pm 0.3) \times 10^{-9}\ \text{MeV}^{-3}]$ is obtained and is in good agreement with the k_{E1} value of $\sim 3 \times 10^{-9}\ \text{MeV}^{-3}$ obtained in previous surveys. A plot of the $E1$ systematics may be seen in Fig. 1. The chi-square value per degree of freedom is large (49) and indicates the presence of structure in the strength function not described by the single-particle picture for this wide a range of nuclides.

If the range of nuclides is limited to $A > 60$, it can be seen in Fig. 1 that the systematics seem reasonably constant. The average value for $k(E1)$ does not change significantly; however, the chi-square value drops to 7.3 indicating a better description of the systematics over this limited mass region.

Axel's approximation, as given by Eq. 7, was then applied to the data. It should be reemphasized that this approximation was derived only for $A \sim 100$, $E_\gamma \sim 7$ MeV, and $\Gamma \sim 5$ MeV. The results are summarized in Fig. 2 for $A > 60$. An average value of $S(E1) = (4.2 \pm 0.4) \times 10^{-15}\ \text{MeV}^{-5}$ is obtained and is somewhat lower than the predicted value of $6.1 \times 10^{-15}\ \text{MeV}^{-5}$. A chi-square value of 6.6 is obtained which is lower than that for the single-particle model calculation for the same mass region indicating that the systematics is somewhat better described for $A > 60$ by an E_γ^5 and $A^{8/3}$ dependence.

A comparison of the data with the predictions of the total photoabsorption cross section was done by taking the ratios of the observed $\langle \Gamma_{\gamma if}/D \rangle$ with those calculated by Eq. (4) for $A > 60$, assuming a constant damping width $\Gamma(E) = \Gamma(E_0)$. The severe fragmentation of the giant resonance for $A < 60$ cannot be reasonably described by a Lorentz approximation. The necessary Lorentz parameters were obtained from Ref. 1 using the criteria that the most recent parameters were used, and,

TABLE II. A list of the surveyed nuclei.

Nucleus [c]	Reference	Comments [a]
^{20}F	24	
^{24}Mg	25	
^{25}Mg	26	
^{26}Mg	27	
^{28}Al [b]	28,24,26	
^{29}Si	29,30	
^{30}Si	29	
^{33}S	24	
^{36}Cl [b]	31	
^{46}Sc	32	
^{53}Cr	33	
^{57}Fe [b]	33	
^{60}Co	34	
^{61}Ni	33	
^{64}Cu	35	
^{74}Ge	36	
^{91}Zr	37	
^{94}Nb	38	
^{93}Mo	39	
^{99}Mo	40	
^{100}Ru	41	
^{102}Ru	41	
^{104}Rh	42	
^{106}Pd [b]		
^{116}In	43	
^{113}Sn	44	Not used, normalized to ^{117}Sn
^{117}Sn	44	Not used, Γ_γ not known
^{118}Sn	44	Not used, normalized to ^{117}Sn
^{119}Sn	44	Not used, normalized to ^{117}Sn
^{125}Sn	44	Not used, normalized to ^{117}Sn
^{122}Sb	45	
^{124}Sb	45	
^{126}Te [b]		
^{128}I [b]		
^{136}Ba	46	
^{139}La	47	
^{140}Ce	48,47	
^{141}Pr	47	
^{142}Nd	47	
^{144}Nd [b]	47	
^{146}Nd	49,50	Renormalized Ref. 49 to intensity of the 454 keV transition given in Ref. 50
^{150}Sm	51	
^{169}Er	52	
^{170}Tm	53	
^{176}Lu [b]	54	
^{178}Hf	55	
^{182}Ta [b]	56	
^{183}W [b]		
^{184}W [b]		
^{196}Pt [b]	57	Renormalized values in Ref. 57 to the values obtained in the present work
^{198}Au	58	Renormalized values in Ref. 58 to those given in Ref. 66
^{199}Hg	59	Renormalized values in Ref. 58 to the Pt values of the present work
^{200}Hg	59	Renormalized values in Ref. 58 to the Pt values of the present work
^{202}Hg	59	Renormalized values in Ref. 58 to the Pt values of the present work

TABLE II. *(Continued.)*

Nucleus [c]	Reference	Comments [a]
^{203}Tl	47	
^{205}Tl	47	
^{207}Pb	27	
^{208}Pb	27,47,60,61	
^{209}Bi	47	
^{233}Th	62	
^{235}U	63	
^{237}U [b]	64	
^{239}U	65	Renormalized values in Ref. 65 to those given in Ref. 66

[a] A complete listing of all the γ-ray transitions included in this survey and all of the parameters that were used in the calculations may be obtained on request from the author.
[b] Indicates nuclides measured in the present work.
[c] Final nucleus.

where the parameters for a particular nuclide were not available, the parameters of the nearest isotope having the same nuclear shape were used. It was assumed that the Lorentz parameters do not change significantly for small variations in A. Where appropriate, the cross section was written as the sum of Lorentzian terms, to include the effects of nuclear deformations. For the ratio [$b(E1)$ measured/$b(E1)$ Lorentz extrapolated] an average value of 0.69 ± 0.06 is obtained. indicating that the calculated values overestimate the experimental data by ~30%. A chi-square value of 6.9 (computed relative to the sample average), is obtained and is somewhat larger than the value of 6.6 obtained using Axel's approximation for the same mass region.

For three nuclides, ^{128}I, ^{136}Ba, and ^{208}Pb, it was found that the most recent parameters listed in Ref. 67 are not in good agreement with those of neighboring nuclides. Therefore, we have taken earlier parameters, also tabulated in Ref. 1, for those three nuclides which give a best fit to the data. The adjusted results are shown in Fig. 3. An average value of 0.70 ± 0.06 is obtained and has a chi-square value of 5.5, computed relative to that average. This is significantly lower than all of the previous values indicating a better description of the systematics.

The chi-square value obtained for these fits indicates that local perturbations from the Lorentzian description are present. Several examples for such local perturbations have been suggested. One such perturbation is the presence of direct capture or valence capture effects in resonances, which can lead to enhancements of the electric dipole strength. This is especially evident in p-wave capture near the $3p$ giant resonance ($A = 90$), and in s-wave capture in nuclei near the $2p(A = 20)$ and $3s(A = 50)$ giant resonances. Another such local perturbation lies in the presence of possible 2p-1h doorway states suggested by Bartholomew and his collaborators,[5,67] near $E_x = 5.5$ MeV for

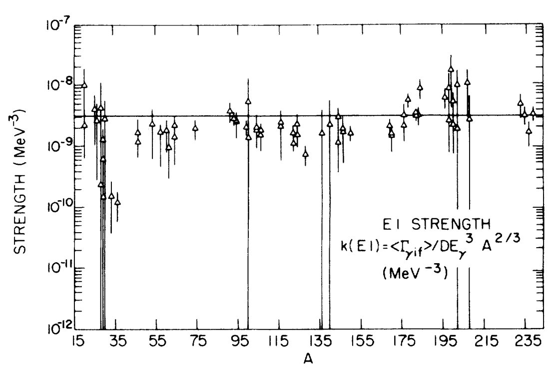

FIG. 1. A plot of the reduced $E1$ strengths against mass number. The average shown corresponds to 0.043 W.u./MeV.

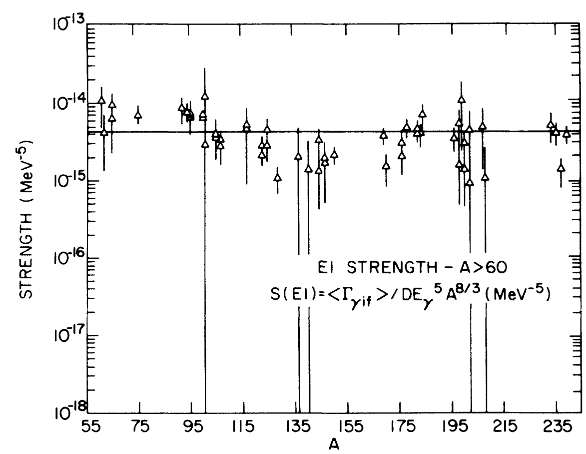

FIG. 2. A plot of the reduced $E1$ strengths using Axel's formulation of reduced strength as shown.

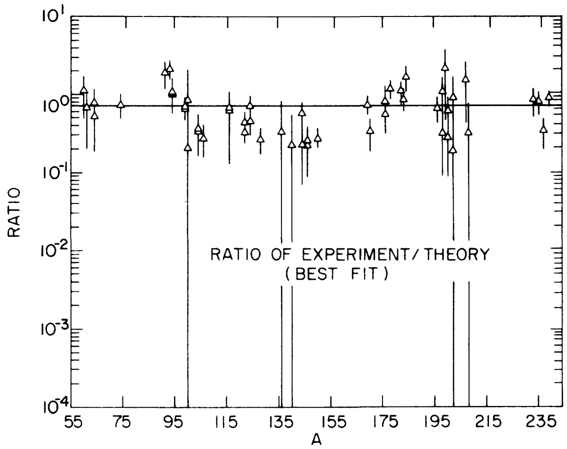

FIG. 3. The ratio of observed $E1$ strengths, defined as $\langle \Gamma_{\gamma if}\rangle /D$ to the Lorentz extrapolated values from photoexcitation experiments. An average ratio of 0.7 is shown.

nuclei ranging from Pb to Ta. We have made no attempt to account for these possible perturbations in the $E1$ strength function.

The use of an energy independent width to describe the tail of the Lorentzian is not consistent with the known damping of the giant resonance. Dover *et al.*[14] suggest a more complicated dependence of the width, which to first order, varies approximately as E^2. Their model is based on a consideration of damped quasiparticle-quasihole excitations. The effect of an energy-dependent width is described below.

B. Magnetic dipole strength functions

The $M1$ photon strength function was investigated for masses ranging from $A = 20$ to 240. Several experimental difficulties occur in the investigation of $M1$ strengths. Since $M1$ widths are typically 5 to 10 times weaker than $E1$ widths corresponding to similar transition energies, they tend to be near the sensitivity limits of resonance capture experiments. Therefore many weak $M1$ transitions can be missed. The resulting bias in the computed $M1$ average width must be carefully accounted for. This correction is reasonably straightforward, given the assumption of a Porter-Thomas width distribution, but the error in the mean width determination is correspondingly increased. Another problem arises from possible competition from $E2$ transitions which may be allowed by the angular momentum-parity selection rules. Fortunately a fair amount of data on the $E2/M1$ mixing ratio exists from thermal capture experiments with polarized neutrons. The average $\delta(E2/M1)$ is found to be on the order of 0.1 (Ref. 68). This low value justifies the neglect of the $E2$ components in the data of this paper.

In Fig. 4 we show the systematic behavior of the $M1$ strength function, $k_{M1} = (\Gamma_{\gamma if}/D)E^{-3}$, as a function of nuclear mass number A. The overall average for k_{M1} is $(3.0 \pm 0.4) \times 10^{-8}$ MeV^{-3}, as obtained from the data of the figure. This value corresponds to previous estimates[5,7] ranging from 4×10^{-9} to 18×10^{-9} MeV^{-3}. The k_{M1} value of the present work is equivalent to a $b(M1)$ value of 1.4 W.u./MeV, and contrasts sharply with the value of 0.05 which prevails for the $E1$ case. There is some indication that the $M1$ strength tends to peak near regions of closed shell nuclei, as indicated by the arrows in Fig. 4, and especially near the region of doubly magic ^{208}Pb. Such enhancement may be explainable in terms of collective spin-flip transitions. An $M1$ giant resonance would also lead to a departure from the expected E^3 behavior for transition probabilities. While such a departure has been claimed[7] for $M1$ transitions following neutron capture in low-resolution experiments, the present survey does not cover enough transitions in any one nucleus, over a sufficiently broad energy space, to establish a departure from an E^3 behavior. Thus the present survey does not offer any support for a concentration of $M1$ strength; in fact the present results are compatible with a uniform distribution of $M1$ strength over the fine structure resonances, and is thus fully consistent with the simple model of Blatt and Weisskopf, in which the single particle strength is uniformly distributed over the fine structure resonances, i.e.,

$$\Gamma_{\gamma if}/D = \Gamma_{sp}/D_{sp},$$

where

$$D_{sp} \approx 1 \text{ MeV} \quad .$$

V. CONCLUSIONS

The present work represents a comprehensive investigation of radiative dipole strength functions

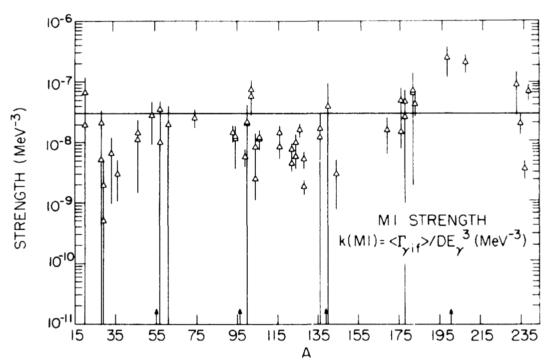

FIG. 4. The reduced $M1$ strengths, defined as shown, as a function of mass number. The arrows indicate regions showing some evidence of enhanced $M1$ strengths.

as derived from discrete resonance capture. Both previous data, renormalized where necessary, and data acquired in the present study have been included to provide a consistent basis for testing theoretical models for the distribution of radiative strength.

The global average of the $E1$ strength function is found to be 0.043 ± 0.004 W.u./MeV. This value can be obtained from a single-particle estimate which assumes that the single-particle state is fragmented into fine structure resonances such that

$$\Gamma_0/D_0 = \Gamma/D,$$

where Γ_0, D_0 represent single particle widths and spacings and Γ, D represent the fine structure widths and spacing. However, a value of $D_0 = 15$ MeV would be required to be consistent with the experimental result. The unreasonably high value of D_0 required is ascribable to a redistribution of $E1$ strength by the giant $E1$ resonance.

A global description of the behavior of $E1$ strengths is rather satisfactorily given by the extrapolation of the giant dipole resonance using a Lorentzain formulation. The global fit is quite reasonable if one excludes the region of nuclei with $A \leq 60$. Both the exact extrapolation of the Lorentzian, and the Axel power law approximation provide reasonable adequate global descriptions. There is, however, a rather significant discrepancy between the strength functions as derived from resonance (n, γ) data and those derived from the giant resonance parameters based on photoabsorption data. The ratio of the measured to predicted (by extrapolation) strength functions is 0.70 ± 0.06.

This observation is most directly interpretable as a failure of the Lorentzian extrapolation of the giant $E1$ resonance to lower excitation energies. The present result supports earlier observations of Bartholomew and his collaborators, and spectral analyses by Gardner and Dietrich.[69] These observations emphasize the fact that capture γ-ray spectra are richer in high energy components that would be predicted by such an extrapolation. The observation that low energy $E1$ transitions below, say 1 MeV, are greatly hindered compared to a Lorentzian extrapolation, is an extreme example of this deficiency. The present work establishes that some deficiency exists even near the neutron separation energy.

The simplest reconciliation of the failure is to include an energy dependent width in the Lorentzian. Axel, in his original formulation of the photon strength function problem, used a Lorentzian form with an energy independent width. Dover, Lemmer, and Hahne[14] have subsequently pointed out the energy dependence of the damping of nuclear dipole states. They consider the effect of collisions between the excited particle-hole pairs and the nuclear background. The effect of such collisions is to replace the undamped particle-hole excitations of the shell model by damped quasiparticle-quasihole excitation whose widths depend on the excitation energy. Dover *et al.*[14] and Arenhovel *et al.*[13] independently suggest a width varying approximately as E^2. Gardner and Dietrich[69] have approached the difficulty in a more empirical way; they assume an energy dependent width in the following expression for the photoabsorption cross section:

$$\sigma_{\gamma a}(E1) = \frac{\Gamma_0(\Gamma_R/2)^2}{(\Gamma_R/2)^2 + (E_\gamma - E_0)^2},$$

where Γ_R refers to the width evaluated at the giant resonance energy E_0. (Gardner and Dietrich refer to this expression as a Breit-Wigner form. However, a proper Breit Wigner form contains the width to the first power in the numerator of the expression for the absorption cross section.) Their expression for the width is approximately linear in energy at an excitation corresponding to the neutron separation energy. However, because they assume an expression for the cross section which contains the square of the width in the numerator, their assumption is equivalent to that of Dover *et al.*[14] and Arenhovel *et al.*[13]

Unfortunately the expression suggested by all these authors yields an energy dependence of the primary electric dipole intensities of E^7, while the experimental data strongly suggest E^5. On the other hand, the discrepancy between the currently determined average strength function and the Lorentz extrapolation can be easily remedied. Ignoring the energy variation in the denominator of the Lorentzian, and assuming a power law expression for $\Gamma(E)$, we have

$$0.7 \approx (E/E_0)^n,$$

$$\Gamma(E) = \Gamma_R(E/E_0)^n.$$

For values of E close to the neutron separation energy, we find $n \approx 0.5$. Thus a square root energy dependence yields an extrapolation which is at once consistent with the measured strength function, and consistent with the observed E^5 dependence of primary γ-ray intensities. The square root dependence would give an $E^{5.5}$ energy dependence, which for practical purposes is indistinguishable from E^5.

The present data say little about the region below the neutron separation energy, where another, more complicated, dependence may be required to satisfy the experiments cited in Ref. 5.

The data cited here on $M1$ strength are much more extensive than previously reported. It also yields an average strength $b(M1) = 1.4$ W.u./Mev which is considerably larger than earlier observations. This value, it must be emphasized, may be unduly influenced by the very large values reported for ^{208}Pb in Ref. 70. If ^{208}Pb is excluded from the sample, the average drops to 0.96 W.u./MeV. Since there is no sum rule applicable for non-self-conjugate nuclei, as in the case of $E1$'s, we can draw no general strength conclusions on the presence of a $M1$ giant resonance. The data are quite consistent with a simple fragmentation picture of single particle resonances. The presence of some structure, and transitions of high strength, near closed shell nuclei, however, provide some evidence for collective enhancement due to spin-flip transitions.

Research has been performed under Contract No. DE-AC02-76Ch00016 with the U.S. Department of Energy.

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