Boson-Broadened Photonuclear Reactions in Light Nuclei

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The giant dipole resonances in light nuclei are described by an intermediate-coupling model which attributes their fine structure and widths to the coupling between single-fermion states and collective bosons associated with the quasistationary stage of the reaction. This model can reproduce details in the giant resonances of O^{16} and Si^{28}, such as the over-all envelopes of the total width, the relative intensities of various major and minor peaks, and the widths of minor resonances.

I. INTRODUCTION

High-resolution experiments on the photonuclear process have revealed considerable structure superimposed on the giant resonances in the light nuclei. Whereas the giant dipole resonance in heavy elements is observed to be a smoothed-out single bump, in light nuclei it is often composed of a number of large resonances. Each one of these resonances may exhibit additional structure, e.g., in the $Si^{28}(\gamma,n)Si^{27}$,[1] $Al^{27}(p,\gamma)Si^{28}$,[2] and $O^{16}(\gamma,n)O^{15}$ [3] reactions. The distinction between the giant resonance profiles in heavy nuclei and in light nuclei requires different techniques of theoretical analysis. The giant resonances in heavy nuclei can be understood reasonably well in terms of a hydrodynamic model.[4] Although the slight structure seen in the medium weight nuclei (e.g., As^{75}) demands a somewhat different explanation in terms of the coupling of the dipole oscillation with the normal modes of the surface vibrations,[5] the underlying physical basis is a pure collective one incorporating the dynamics of the nuclear fluid motion. However, neither a hydrodynamic model nor a particle-hole model using a spherical or deformed potential (with an appropriate residual interaction[6]) can alone adequately explain the location, widths, or shape of the major and minor peaks in light nuclei. Recent attempts[7] to attribute the widths of the broad peaks to the coupling of the giant resonance states to the continuum provide only a qualitative understanding without any attempt to explain the detailed structure of the giant resonance. It is generally the case in nuclear physics, however, that many observed properties such as level schemes, moments, and transition rates cannot be understood both in the heavy- and in the light-mass regions in terms of a single model. In heavy nuclei, these properties are often more appropriately described by a collective model, whereas many properties of light nuclei admit either a pure single-particle approach or a dual description of both a collective and an independent particle nature. It is therefore possible that such a "dualism" is to be incorporated in any description of the giant resonance in light nuclei. In lighter nuclei, the structure of the giant resonance may embody a modification of the pure collective picture by incorporating the independent particle aspect of the "dualism" that is inherent in them. There is, in fact, considerable evidence consistent with the assumption that the photonuclear processes in light nuclei display some features typical of independent-particle behavior: (a) the admirable attempt to understand the structure in $Al^{27}(p,\gamma)Si^{28}$ [2] in terms of a statistical fluctuation[8] around the mean envelope led to the interesting result that the direct component part (or the fast component) of the reaction constitutes 96% of the total cross section. (b) Moreover, a meaningful analysis of the fluctuation required treating the entire giant resonance region of Si^{28} in three distinct parts, which cannot therefore rule out the possibility that the giant resonance in Si^{28} may be composed of three distinct resonances. (c) A recent experiment[9] has indicated that the neutron yields from $Si^{28}(\gamma,n)Si^{27}$, $O^{16}(\gamma,n)O^{15}$, and $C^{12}(\gamma,n)C^{11}$ have pronounced high-energy tails extending beyond 50 MeV.

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[8] T. Ericson, Advan. Phys. **9**, 425 (1960); Ann. Phys. (N. Y.) **23**, 390 (1963); D. M. Brink and R. O. Stephen, Phys. Letters **5**, 77 (1963); W. R. Gibbs, Los Alamos Scientific Laboratory Technical Report No. LA-3266, 1965 (unpublished).

[9] F. W. K. Firk, in Proceedings of the International Conference on Nuclear Physics, Gatlinburg, 1966 (unpublished).

While this tail undoubtedly contains transitions of higher multipolarity than the dipole, both the energy dependence and the fact that only a part of the dipole sum is used up by the giant dipole resonance suggest that a reasonable amount of dipole absorption takes place in this tail region. Yields of such high-energy neutrons in a dipole transition are compatible with a direct reaction mechanism involving one or a few particles only.

An extreme single-particle model, on the other hand, cannot account for the structure of the giant dipole resonance.[10] A direct transition from the ground state to the continuum forms a smoothly varying cross section, whereas a direct emission via a well-defined single-particle state would result in a single sharp resonance having a width of the order of single-neutron emission width.

The purpose of this paper is to suggest an intermediate mechanism displaying the dualism of the independent-particle and of the collective aspects simultaneously and to investigate how far such a model can explain both the detail and the gross structure of the giant resonances in O^{16} and Si^{28}.

It is interesting to recall that an analogous situation, depicting simultaneously the roles of the independent-particle and of the collective aspect, exists in the photo- (and inverse) absorption process in solids.[11–13] When an incident electron is captured in a solid, the absorption line shape is observed to be considerably broadened and the shape of the cross section bears considerable similarity to that obesrved in some photonuclear reactions. The explanation of this broadening involves the interaction of the single electronic state with a phonon mode of the lattice, set in vibration by the presence of the electron. The single electronic width is broadened as a result of this coupling (interaction). In fact, the broadening of the single-particle (or fermion-state) width by a collective (or boson) field forms one of the bases of the general theory of the line shape, and is a well-established concept. Although the physical situation underlying the photonuclear process may be different from the phonon broadened absorption in a solid, the magnitudes of the basic constants (such as the single-particle energies, the density of collective excitations, etc.) in the photonuclear process bear a similarity to the solid-state case, if one translates the energy unit of eV, appropriate to solids, to MeV, appropriate to nuclear physics. In Sec. II we develop the theory pertinent to a model for a photonuclear reaction which is analogous to phonon-broadened electronic transition in solids. In Sec. III we apply this model to the giant resonance region of O^{16} and Si^{28}.

II. THEORY

A photon, incident on a nucleus, can excite a nucleon so that it moves in the mean nuclear potential generated by the excited nucleus. The potential in which the excited nucleon moves is, of course, different from that which it experiences when the system is in its ground state. The motion of the single excited particle is governed by a fermion field, whereas the excitation of the core, being of a collective nature, is described by a boson field. Furthermore, the particle state must, in principle, be coupled to the collective state of the core (otherwise there cannot be a core excitation at all). The presence of the particle influences the core firstly by interacting with it in an average way, thereby changing the average potential in a self-consistent fashion, and secondly by polarizing the core. It is to be noted that the change in the self-consistent field depends on the quantum state of both the excited particle and the core. In other words, the fact that the wave functions of single-particle states in an independent-particle model depend on the radius of the potential (and more generally on its shape, if one uses a nonspherical potential) leads automatically to a dependence of the excitation energy of a particle (or particle-hole quasiparticle) state on the fractional deviation of the nuclear radius in the excited state from its value in the ground state.

Thus the model Hamiltonian of a particle moving in the presence of a core is given by

$$H=H_0+H_T\,, \tag{1a}$$

where

$$H_0=\sum_{\lambda=0}^{1}\{C_\lambda^\dagger C_\lambda E_\lambda^{(0)}+\sum_\alpha[\hbar\omega_{\alpha\lambda}(b_{\alpha\lambda}^\dagger b_{\alpha\lambda}+\tfrac{1}{2})+C_\lambda^\dagger C_\lambda g_{\alpha\lambda}\hbar\omega_{\alpha\lambda}(b_{\alpha\lambda}+b_{\alpha\lambda}^\dagger)]\}\,, \tag{1b}$$

$$H_T=\langle\lambda'|T|\lambda\rangle C_{\lambda'}^\dagger C_\lambda+\text{c.c.} \tag{1c}$$

The $C_\lambda^\dagger$ and $b_{\alpha\lambda}^\dagger$ are creation operators for the fermion field associated with the particle motion and for the boson field associated with collective motion of the core, respectively. $E_\lambda^{(0)}$ and $\hbar\omega_{\alpha\lambda}$ are the fermion and boson energies. Moreover, we have assumed the coupling between the fermion (or particle) and the boson fields to be linear with a coupling strength $g_{\alpha\lambda}$. Such a linear coupling amounts to keeping only the first-order term in the expansion of potential surface of the excited core in terms of the potential surface of the core in its "ground state," as noted by Bohr and Mottelson[14] and

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[14] A. Bohr and B. R. Mottelson, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. **27**, No. 16 (1953).

by others.[15,16] Alternatively, the first-order term in the Taylor's expansion of the boson energy quantum associated with the excited state may be written in terms of that associated with the ground state of the core.[17] This gives rise again to a linear coupling term.

The Hamiltonian H_0 describes the upper and the lower fermion states coupled to their respective boson fields. We shall denote the quanta of collective excitations as "collectons" by analogy with phonons in solids. The term H_T is responsible for the excitation of the intermediate state via γ-ray absorption. If the transition is predominantly electric dipole, T is the electric dipole operator. We may use the standard Condon approximation,[13] so that the boson coordinates do not occur in H_T.

The Hamiltonian H_0 may be diagonalized by a canonical transformation,[13,18] and leads to the single-fermion eigenvalues and eigenvectors

$$E_\lambda = E_\lambda{}^{(0)} - \Delta_\lambda + \sum_\alpha \hbar\omega_{\alpha\lambda}(n_{\alpha\lambda}+\tfrac{1}{2}), \tag{2a}$$

$$\Delta_\lambda = \sum_\alpha [|V_{\alpha\lambda}|^2/\hbar\omega_{\alpha\lambda}], \tag{2b}$$

$$|\Psi_\lambda\rangle = \exp(S_\lambda)C_\lambda{}^\dagger|\{n_{\alpha\lambda}\}\rangle, \tag{3a}$$

$$S_\lambda = \sum_\alpha \{[V_{\alpha\lambda}b_{\alpha\lambda} - \bar{V}_{\alpha\lambda}b_{\alpha\lambda}{}^\dagger]/\hbar\omega_{\alpha\lambda}\}, \tag{3b}$$

$$|\{n_{\alpha\lambda}\}\rangle = \prod_\alpha \frac{(b_{\alpha\lambda})^{n_{\alpha\lambda}}}{\sqrt{(n_{\alpha\lambda}!)}}\left|0\right\rangle, \tag{4}$$

$$g_{\alpha\lambda}\hbar\omega_{\alpha\lambda} = V_{\alpha\lambda}. \tag{5}$$

The energy Δ_λ measures the shift of the single-particle excitation due to the coupling of the fermion state with the collective motion. Since it is analogous to the polaron shift in solids, we refer to it as the "collecton shift." Because of this collecton shift, the location of the experimentally observed fermion state is different from the position of the fermion state in the average nuclear potential. The factor S_λ describes the "collecton correlation" in the wave function which causes the total transition strength associated with a pure transition (i.e., the absence of any collective motion) to spread out into a band of collectons plus the single-particle states (in the spirit of Lane, Thomas, and Wigner[19]). This term is directly responsible, therefore, for the broadening of the transition width. The measure of this broadening is the density of states at a temperature $\theta = (\beta k)^{-1}$, which is given by

$$\rho_\beta{}^{(-)}(\lambda,E) = (2\pi\hbar)^{-1} \times \int_{-\infty}^{+\infty} \exp\left\{\frac{i[E+E(\lambda)]t}{\hbar}\right\} g_\beta{}^\lambda(t)dt, \tag{6a}$$

$$E(\lambda) = E_\lambda{}^0 - \Delta_\lambda, \tag{6b}$$

$$g_\lambda{}^\beta(t) = \exp\left\{-\sum_\alpha \left|\frac{V_{\alpha\lambda}}{\hbar\omega_{\alpha\lambda}}\right|^2 ([\langle n_{\alpha\lambda}\rangle+1] \times[1-\exp(-i\omega_{\alpha\lambda}t)] + \langle n_{\alpha\lambda}\rangle[1-\exp(i\omega_{\alpha\lambda}t)])\right\}, \tag{6c}$$

$$\langle n_{\alpha\lambda}\rangle \equiv [\exp(\beta\hbar\omega_{\alpha\lambda})-1]^{-1}. \tag{6d}$$

It may be noted that the model Hamiltonian (1a) which contains fermion and boson states is distinctly different from the one used by Danos and co-workers.[5] The latter deals only with motion of a collective type.

Henceforth, we confine our attention to the special case of the coupling to a single boson field with finite frequency and replace $\omega_{\alpha\lambda}$ by ω_λ and the coupling constant $V_{\alpha\lambda}$ by $V_\lambda = g_\lambda\hbar\omega_\lambda$. (We retain the subscript λ because the giant resonance cross section consists of combinations from several separate single-particle excited states.) In this case it is well known[13] that a simple line spectrum for $\rho_\beta{}^{(-)}(\lambda,E)$ occurs and we get

$$\rho_\beta{}^{(-)}(\lambda,E) = \exp[-g_\lambda{}^2(2n_\lambda+1)] \sum_{d=-\infty}^{\infty} \delta[E+E(\lambda)-d\hbar\omega] \times((n_\lambda+1)/n_\lambda)^{d/2} I_d\{2g_\lambda{}^2[n_\lambda(n_\lambda+1)]^{1/2}\}, \tag{7a}$$

$$n_\lambda = [\exp(\beta\hbar\omega_\lambda)-1]^{-1}. \tag{7b}$$

$I_d(x)$ are the modified Bessel functions. We also have

$$\int_{-\infty}^{+\infty} \rho_\beta{}^{(-)}(\lambda,E)dE = 1. \tag{8}$$

The model attributes the width of the profile of the giant dipole resonance to the broadening of single-particle transitions between two fermion levels, due to the coupling of the fermion levels to the collective excitation. That such a broadening occurs in the presence of a coupling between the single-particle state and collective states is a well-known effect in physics. The linear coupling of particle motion to the collective excitation is well acknowledged in the field of nuclear physics.[14–16]

It is worth noting that the characteristic broadening of the line shape due to a linear coupling between a fermion and a boson field exhibits an asymmetry, which is indeed observed in the two examples investigated below.

We have not as yet specified the character of the single-fermion levels in any detail. They may be Hartree-

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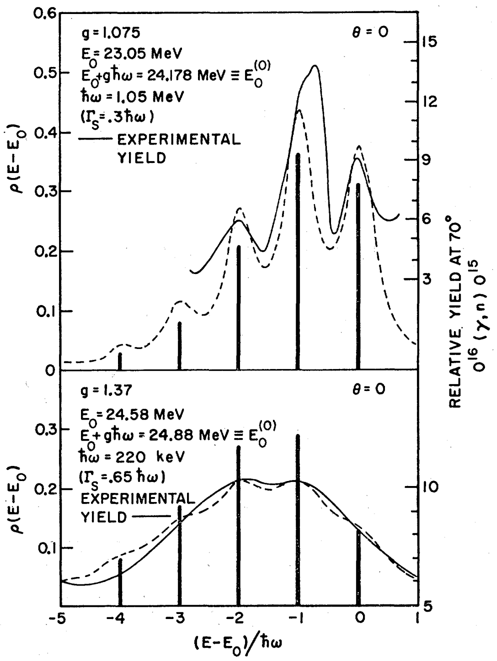

FIG. 1. The heavy solid lines give the intensities of the spectral lines obtained from Eq. (7a). The lightly dashed line gives the intensities expected if the single-fermion state has a width Γ_S. The light solid line indicates the high-resolution neutron yield for reaction $O^{16}(\gamma,n)O^{15}$ obtained by Firk (Ref. 3). All theoretical parameters are indicated in the figure.

Föck, shell-model, Nilsson-model, or any kind of fermion states which can be generated from an independent-particle model by the inclusion of a residual interaction in quasiparticle approximation. The only important criterion for the purpose of this model is to define the single-particle states as states whose creation and annihilation operators obey the Fermi commutation relation.

We also have not specified the collecton states in detail. The simplest model for them is, of course, the density oscillations whose frequency is determined by the excitation energy and nuclear compressibility. Such oscillations carry no angular momentum, so that the use of the Condon approximation for H_T is reasonable for them. A more common variety of oscillations are surface waves which occur even for an incompressible Fermi liquid. The boson field may also represent only a partial excitation of the core in the form of a cluster excitation, e.g., the $2p$-$2h$ or multiparticle-multihole excitation. This is relevent to the collecton states in O^{16}. The rotational excitation[20] of the core may form yet another kind of collective excitation; in the limit of high excitation and small moment of inertia, they can be considered to have almost uniformly spaced excitation spectrum and in that limiting case, it is consistent with our model for the boson field.

[20] F. Beck and G. Kluge (private communication).

In the present investigation, the question of collectons associated with the ground state does not arise, since the single-particle state is coupled to a boson field associated with the excited nucleus.

III. APPLICATION

Only the high-resolution photonuclear experiments, which can distinctly separate the broadened single-particle levels, are suitable for the analysis in terms of the above model. We consider here, in particular, applications to the fine structure of the giant resonance in the excited Si^{28} and O^{16} nucleus. There are three natural parameters entering the computation of the linewidth involving a single excited fermion state. These are (a) the energy of the fermion level, (b) the frequency associated with collective boson field, and (c) the coupling strength between the fermion and the boson fields. A successful model for understanding the giant resonance must aim in the first place to account for the broad features like (a) the over-all width of the total giant resonance (b) the widths of fairly separated broad major bumps (or resonances), and (c) the relative intensities of the major peaks. Additional explanations of the fine structure on the envelope of a major peak (if present) and of the basic parameters in terms of other models would provide further confidence in the model.

The reaction $O^{16}(\gamma,n)O^{15}$ provides a good test of the collecton model, because the detailed structure observed in the neutron-yield curve does not admit an interpretation either in terms of Ericson's fluctuation or in terms of the Elliott and Flowers model[6] or in terms of a simple hydrodynamic model.[4] The single-particle width which was assumed to be a δ function in (6) and (7) must in principle be finite and consequently a normalized Lorentzian width of Γ_S related to the lifetime of the fermion state in the absence of the coupling term has been attributed to them.

A major difficulty in understanding the structure of the giant dipole resonance in O^{16} has been the fact that the single-particle or the particle-hole descriptions predict the location of only two well-separated single-particle states in the excitation energy region considered in Fig. 1, whereas the neutron yields show four distinct resonances, along with some fine structure on some of them. The recent measurement[21] of the angular distribution of the γ rays in the $N^{15}(p,\gamma_0)O^{16}$ reaction indicates that more than 90% of the strength in the giant resonance is consistent with a pure dipole ($E1$) transition, thus ruling out the possiblity of identifying some peaks with $E2$ or higher multipole transition. The present model provides a mechanism to account for this paradox; in Fig. 1, both the computed curve and the experimental observations have been plotted. The most interesting feature of this model is to be able to account for all the major as well as minor bumps—it is sufficient

[21] N. W. Tanner, G. C. Thomas, and E. D. Earle, Nucl. Phys. **52**, 29 (1964).

TABLE I. Estimates of the collecton quanta obtained from the classical liquid-drop model of Ref. 20 using $\Gamma = 18$ MeV, $K = 4$ MeV, and $r_0 = 1.2$ F.

Excitation energy (MeV)	Collecton energy (keV)			
	O^{16}		Si^{28}	
	Surface	Volume	Surface	Volume
17	59	195	20	81
19	42	130	12	50
21	30	88	8	32
23	21	60	6	20
25	16	40	4	13

for this model to have *only two* 1− fermion states in this energy region and the fermion transition strength is then distributed over various boson states via the coupling term. The parameters of our calculation have been listed in the figure. Already two of these parameters, i.e., the location of the single-particle 1− states, have been justified from a number of shell-model calculations (e.g., see Ref. 6). An estimate of the collecton frequencies can easily be done for the idealized case of treating nuclear matter as fluids.[22] Table I provides such an estimate. It is worth noting that this estimate is also consistent with the other extreme of treating nucleons as free fermions interacting by a two-body interaction.[23] However, the estimate of the average spacing of the energy levels in terms of the pure hydrodynamic model represents a highly idealized case for O^{16} at 20- to 25-MeV excitation energy and may only be used to get the correct order of magnitude. Actual "collecton excitation" in O^{16} must be identified with only partially excited collective modes such as cluster (α particle) as $2p$-$2h$ or multiparticle-multihole excitation and therefore the actual boson frequency is expected to be larger than the hydrodynamic estimate.[24] By the use of a large collecton energy, permitted by the uncertainty in the estimates of Table I, we can achieve the description of the three-line structure near 22-MeV excitation energy the highest peak at 22.3 MeV is then not a single-particle peak but corresponds to the emission of a single collecton. The success of this fit to the profile of the giant resonance leads to the conclusion that the giant resonance in O^{16} is not due to the oscillation of all protons against all neutrons but represents an enhancement of a dipole radiation between two fermion levels due to a coupling with the collective mode.

An interesting refinement of this basic model would occur if one wants to couple the fermion states with two kinds of boson fields, e.g., one with spin zero and another with spin two. In that case an alternative interpretation of the line shape of 22.3 MeV is possible by ascribing this as due to the coupling of the fermion levels with bosons

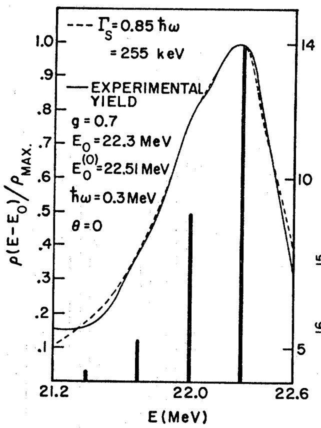

FIG. 2. The heavy solid lines show the intensities of the spectral lines obtained from Eq. (7a) normalized so that the highest-intensity line gives unity. The lightly dashed line gives the normalized intensity obtained when the δ functions in Eq. (7a) are replaced by Lorentzians of width Γ_S. The light solid line indicates the high-resolution neutron yield for the reaction $O^{16}(\gamma,n)O^{15}$ obtained by Firk (Ref. 3). All theoretical parameters are indicated in the figure.

of zero spin. The observed slight asymmetry shape of this line (which is characteristic of the line broadening due to a linear coupling between a boson and fermion field) can be reproduced using a higher density of states as shown in Fig. 2. In that case, the two adjacent peaks are to be ascribed to the coupling of the same fermion state to the boson field with angular momentum two. A detailed theoretical investigation on this sophisticated line is only warranted if (i) the suggestive presence of some fine structure[3] on the low-energy side of the 22.3-MeV line and (ii) the spins of the adjacent two resonances are first experimentally established.

The reactions $Si^{28}(\gamma,n)Si^{27}$ [1] and $Al^{27}(p,\gamma)Si^{28}$ [2] reveal a large number of narrow peaks within three broad major resonances; such structure is well suited to an analysis using the present model. Figure 3(a) shows the experimental measurement of the neutron yields from $Si^{28}(\gamma,n)Si^{27}$ (Ref. 1). (Two points should be noticed: This experiment may contain neutrons from non-ground-state transitions and the resolution around 18.0-MeV excitation energy is considerably better than that at higher energies.) The interesting features of the experiment are: (a) There seem to be three well-separated broad major resonances, and (b) the spacing of the individual small or minor peaks associated with an individual small or minor peaks associated with an individual broad resonance is fairly uniform for a particular major resonance, which is analogous to the typical feature of phonon broadened electronic transition in solids due to low-energy vibration.

The particle-hole calculations[25] indicate the presence of three fermion 1− states for excitation of 17–21 MeV in Si^{28}. From Table I, the expected collecton energy lies

[22] H. A. Bethe, Rev. Mod. Phys. 9, 69 (1937). The estimate in the text is obtained in using Eqs. (284) and (322), replacing the exponent $n/2$ in Eq. (284) by its correct value $1/2n$.
[23] J. Bardeen, Phys. Rev. 51, 799 (1937).
[24] V. Gillet (private communication). It is reported that a preliminary computation indicates that the average spacing of $(2p-2h)$ states in this excitation energy is of the order of 1 MeV.

[25] J. B. Seaborn and J. M. Eisenberg, Nucl. Phys. 63, 496 (1965).

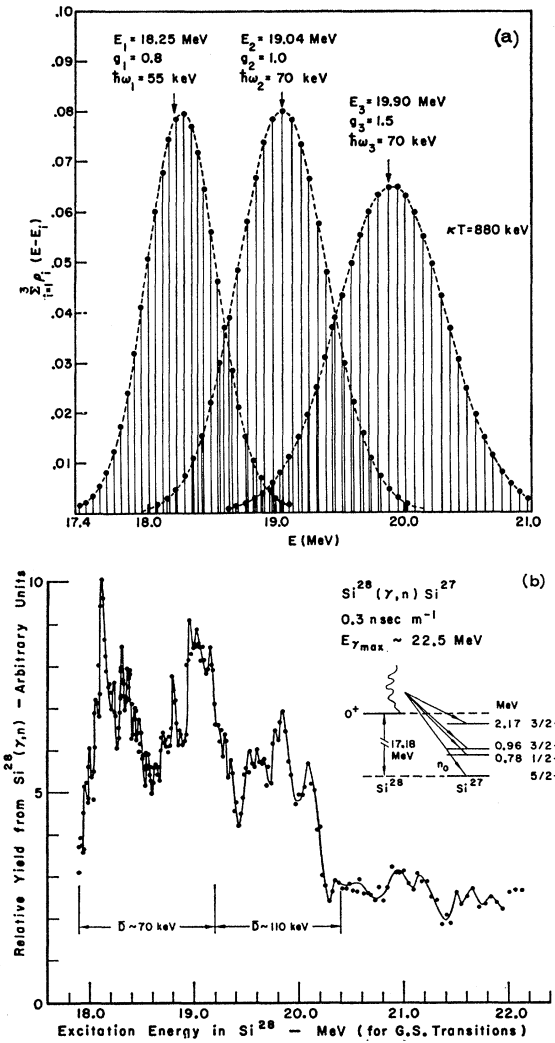

FIG. 3(a) The vertical solid lines give the intensities of the spectral lines obtained from Eq. (7a). The lightly dashed line is inserted as a visual aid to locate the envelope of the sharp-line spectra. The collecton-shifted fermion energies E_λ, collecton energies $\hbar\omega_\lambda$, coupling constants g_λ, and nuclear temperature θ are indicated in the figure. (b) The experimental neutron yield obtained for the reaction $Si^{28}(\gamma,n)Si^{27}$ by Firk (unpublished). The yield below 19 MeV may be artificially enhanced by the inclusion of non-ground-state transitions.

between 30 and 80 keV. In Fig. 3(b) the computed line-shape spectrum is presented assuming that the entire giant resonance is composed of three well-defined collection broadened single-particle states at 18.25-, 19.04-, and 19.90-MeV excitation energy, respectively, which are consistent with the above-mentioned computation of three fermion states. There is not much choice in the boson frequency, because if the model is correct, the average spacing of small peaks must be the boson frequencies. The actual values used for the boson frequencies are 55 and 70 keV for the first and the last two resonances, respectively, which are again consistent with our estimate given in Table I. (It may be noted that the observed level density below 19-MeV excitation energy may be artificially enhanced by the inclusion of non-ground-state transitions.) It would clearly be helpful to resolve this experimental difficulty and to improve the resolution at higher energies. In the Si^{28}, we have further reduced the number of parameters by assuming the idealized case of a sharp fermion state (i.e., $\Gamma_S=0$). Once more, the agreement with the experiment is satisfactory.

While in the case of O^{16} we use a zero temperature (i.e., $\theta=0$), the computed spectrum of Si^{28} is given for $\theta=880$ keV; however, essentially the same line-shape spectrum can be obtained for zero temperature using a somewhat larger coupling constant.

Without further computation one expects, within the framework of this model, a systematic change in the character of the observed structure across the periodic table. Because of the large single-fermion width, the fine structure due to the excited state collectons in light nuclei is expected to be smeared out as in O^{16} (Fig. 2). As we consider heavier nuclei from $\sim C^{12}$ to $\sim Ca^{40}$, the two systematic modifications of the intrinsic parameters take place: (1) The fermion natural widths Γ_S decreases rapidly for those states in the photonuclear process.[26] (2) Both the excited- and ground-state collecton energies decrease with A, but less rapidly than Γ_S. Because of these and of the finite resolution of the experiments, the fine structure due to excited-state collectons can no longer be observed beyond $A\sim 40$ or 50, and one would see a single bump. However beyond this mass region, it becomes important to consider the presence of the collectons in the ground state which introduces automatically a quadrupole (or higher) coupling between collective states which then dominates the structure of the giant resonance.[5] For heavier nuclei the temperature is reasonably high, so that one reaches the idealized case of extreme collective oscillations and the single-particle aspect is no longer important.

ACKNOWLEDGMENTS

We wish to thank Dr. J. E. E. Baglin and Dr. P. F. Yergin for fruitful discussions.

[26] See, e.g., E. Hayward, *Nuclear Structure and Electromagnetic Interactions in Proceedings of Scottish Universities Summer School*, edited by N. MacDonald (Plenum Press, Inc., New York, 1965), p. 141.