Recent evidence for giant dipole resonances built on all states statistically populated in heavy ion reactions is reviewed, with emphasis on outstanding difficulties and problems. Some new directions are suggested.

The giant dipole resonance (GDR) built on the nuclear ground state has been studied over the course of almost 40 years with a variety of probes. This resonance is produced by a coherent superposition of 1 particle–1 hole excitations, centered at roughly $77 \ A^{-1/3} \ (\text{MeV})$ in excitation. In 1957 Brink showed that this microscopic model is completely equivalent to the hydrodynamic description of a proton fluid that oscillates against the neutrons after absorbing a dipole photon. In statically deformed nuclei, the hydrodynamic theory predicts a splitting of the GDR into two components corresponding to the characteristic frequencies for oscillation along the different axes of a spheroid. This effect has been observed in a number of heavy nuclei and serves as a measure of nuclear deformation. (Further splittings due to the effects of isospin can also occur but are generally much less dramatic.)

Very little is known about giant dipole excitations built on excited states of nuclei. Brink has proposed that a GDR should exist for every excited state and that the shape of the dipole strength function should be largely independent of the detailed structure of the initial parent state. For the most part this hypothesis has been tested only for low lying states whose wavefunctions are very similar to that of the ground state. Recent data from proton capture on light nuclei, leading to particle–hole states of modest excitation (15–20 MeV) and relatively low
spin, have revealed GDRs at energies nearly the same as that of the ground state GDR but with dramatically increased widths. Although this increase in width seems to track the complexity of the nuclear wavefunction of the parent state with excitation energy, the detailed behavior is by no means understood.

Until very recently, no information was available on the nature of dipole strength functions in the continuum at high energies (~ 50 MeV) and at high spins (~ 30 h). One might well have guessed a dipole strength distribution so spread out as to be unrecognizable as a resonance. It was thus quite surprising to observe that statistical gamma ray spectra produced in heavy-ion fusion reactions populating regions of high spin and excitation could, for the most part, be accounted for by ground-statelike GDRs built on all nuclear levels in the continuum. An extrapolation of the hydrodynamic model suggests that such reactions might yield information on the properties of rapidly rotating heated nuclei in a region not accessible to the spectroscopy of discrete states.

Examples of the experimental observations are presented in Figure 1 where the gamma ray spectra from the fusion reaction $^{34}$S + $^{130}$Te leading to $^{164}$Er and from the reaction $^{29}$Si + $^{124}$Sn leading to $^{153}$Gd are histographed. In the energy range below 10 MeV, both spectra show a simple exponential falloff characteristic of transitions deexciting statistically populated nuclear levels with a constant matrix element. However, about 12 MeV there is a considerable excess of gamma ray yield over this exponential (denoted by the dashed lines).

The solid curves through the data of Figure 1 were calculated using a statistical evaporation code assuming that all gamma ray transitions are $E1$ and that the dipole strength associated with each state follows a Lorentzian distribution with shape parameters similar to the GDR built on the ground state of the compound nucleus. More specifically, the gamma ray width associated with a state of spin $J$ at an energy $E$ was assumed to follow the form:

$$\Gamma(J,E) = \frac{(20.9 \times 10^{-6}) S NZ}{2\pi A} \sum_{J}^{J+1} \frac{\int_{0}^{\infty} \frac{\rho(E - E_{\gamma};J)}{\rho(E;J)} \frac{\Gamma_{E_{\gamma}}^{4} dE_{\gamma}}{(E_{\gamma}^{2} - E_{R}^{2})^{2} + (\Gamma E_{\gamma})^{2}}}{\rho(E;J)}$$

where $S$ is the fraction of a classical dipole sum rule represented by the above distribution. In this model highly excited states which are them-
selves giant dipole resonances built upon lower lying excited states are statistically populated. The gamma decay from these highly excited levels appears enhanced simply because the gamma ray strengths associated with these GDRs peak near a common transition energy $E_R$. For the case of the $^{34}\text{S} + ^{130}\text{Te}$ reaction shown in Figure 1 the calculation assumed a resonance width $\Gamma = 13$ MeV, a centroid $E_R = 17$ MeV and the full dipole sum rule ($S = 1$), while for $^{29}\text{Si} + ^{124}\text{Sn}$ the calculation assumed $\Gamma = 11$ MeV, $E_R = 15$ MeV and 1/3 of a classical sum rule.

**FIGURE 1** Statistical gamma ray spectra from two heavy-ion fusion reactions (Ref. 5). The dashed lines extrapolate the low energy exponential behavior. The solid curves are the result of calculations using the statistical evaporation code CASCADE (Ref. 6), assuming that each nuclear level has a giant dipole resonance associated with it (see text). In these calculations a search was made for the best possible description of the data between 7 and 22 MeV.
The study of these giant resonancelike structures observed in gamma ray spectra following heavy-ion reactions is currently underway in a large number of laboratories throughout the world, reflecting the high level of interest in this phenomenon. However, a disturbingly large range of resonance parameters have been “extracted” from reactions that are very similar. This is partly because a variety of different criteria have been used for defining an acceptable fit of calculation to data, and partly because the resonance parameters which enter these calculations are far from independent in the determination of the final gamma ray spectrum. The deduced resonance parameters are also very sensitive to the experimental conditions in which the spectra are obtained. It is useful to note that in the calculations presented in Figure 1 the set of possible solutions for $S$, $E_R$ and $\Gamma$ is greatly restricted by the absolute normalization (which is known to better than 20% in the case of Figure 1), efficient neutron rejection (which strongly affects both the magnitude and slope of the data) and the shape of the spectrum above about 18 MeV (for which good cosmic ray rejection is crucial). Furthermore, the overall slope of the spectra and thus the resulting parameters can be significantly altered if small detectors are used without active shields (so that the products from high energy showers can leave these crystals undetected), resulting in a gamma ray response with substantial tailing to lower energies.

Two observations can be made from the analysis shown in Figure 1 (see also Refs. 4 and 8). First, considering the extremely high excitation energies involved (over 60 MeV in the compound nuclei) it is amazing that the fitted widths are not considerably broader. On the other hand, the deduced resonance parameters are considerably altered from those of the GDRs built on the $^{164}$Er and $^{153}$Gd ground states. Photoabsorption on the closest neighboring nuclei for which data exist is shown in Figure 2 (from Refs. 9 and 10). $^{152}$Gd is a deformed rotor exhibiting the classical hydrodynamic splitting. $^{166}$Er is also deformed but a strong coupling to low lying vibrational and rotational levels further splits the GDR into several components. The resonance widths extracted from the fits to the data of Figure 1 are double the ground state values, and in the case of $^{34}$S + $^{150}$Te the centroid is shifted up significantly. This increased width for GDRs built on excited states is consistent with the recent results from proton radiative capture to discrete levels in lighter nuclei. The sum rule fraction extracted from the $^{29}$Si + $^{124}$Sn data ($S = 1/3$) is considerably smaller than that from the $^{34}$S + $^{130}$Te reaction ($S = 1$).
FIGURE 2 The giant dipole resonance built on the ground states of erbium (Ref. 8) and gadolinium (Ref. 9) as seen in photoabsorption.

It is interesting to note that this reduction follows the same trend observed in the ground state GDRs. In Figure 2 the erbium spectrum exhausts 1.1 sum rules, while absorption by gadolinium accounts for only 0.6 of a sum rule. This tendency of extracted sum rules to follow those of the ground state GDRs has also been observed in reactions leading to lighter compound nuclei. However, the number of systems studied so far is rather few and more data are certainly needed to study this phenomenon. The resonance parameters deduced from the present analyses represent an average over a tremendous number of states varying over a wide range of spins and excitation energies. Because of this inherent averaging the differences between the $^{34}\text{S} + ^{130}\text{Te}$ and the $^{29}\text{Si} + ^{124}\text{Sn}$ systems, which are so close in mass, are quite unexpected and merit attention.

The second observation to be made is that intermediate structure, such as is evident in the ground state GDRs of Figure 2, does not appear
in these heavy-ion fusion gamma ray spectra. It should be remembered
that spectra such as those shown in Figure 1 are made up of contributions
originating at all steps of the decay cascade of the compound nucleus
with a very broad distribution of initial spins. If the GDR strength
function is strongly energy or spin dependent, this might well obliterate
any intermediate structure.

Recently Egido and Ring\textsuperscript{12} calculated the shape of the GDR in \textsuperscript{164}Er
as a function of angular momentum, assuming the first order hydro-
dynamic description resulting in two peaks for the ground state reso-
nance (see also Ref. 13). Their results, separated into the components
corresponding to vibrations parallel ($K = 0$) and perpendicular ($K = \pm 1$)
to the nuclear symmetry axis in the rotating frame, are shown in Figure
3. The lowest curve of each set corresponds to $I = 0$; the others to
$I = 6, 12, \ldots, 60 \hbar$. With increasing angular momentum, the GDR
peak positions move and the $K$ components mix as the Coriolis field
increases. In fact the peaks separate, which leads to a larger GDR width
at high spin. It is clear from Figure 3 that the amount of intermediate
structure observable in the gamma decays of these GDRs will be drasti-
cally reduced when the various $K$ components are summed and when
there is an integration over spin. Not only is this summation and in-
tegration inherent to fusion reactions, but in these reactions there is also
a summation over many residual nuclei produced by particle emission.
It is doubtful that such inclusive gamma ray measurements will ever be
able to observe pronounced structure related to deformation splitting.
On the other hand, Figure 3 suggests that some structure could persist
after the $K$ summation if there is some selectivity on the range of initial
spins. Such a selectivity has been achieved in partially exclusive ex-
periments by using a sum spectrometer\textsuperscript{4} or a multiplicity filter\textsuperscript{14} as a
gate for the high energy gamma rays. In such measurements an overall
enhancement of the high energy gamma ray yield seems to be associated
with lower spins,\textsuperscript{4,14} but little qualitative variation is observed in the
shapes of the spectra and no intermediate structure is evident. This
apparent contradiction with Figure 3 may result from the fact that the
present calculations do not properly include the effects of $2p-2h$ states
or more complicated configurations which are important at high exci-
tation energies. As seen in the erbium absorption spectrum of Figure
2, these effects can drastically alter the shape of the dipole resonance
from the simple first order hydrodynamic prediction.
It is clear from the above discussion that the effects of nuclear deformation upon gamma ray spectra obtained from heavy-ion fusion reactions will be quite subtle. There may already be an indication of this in Figure 1. Although the solid curves pass through the average of the data, there are systematic discrepancies which appear small only because it is the logarithm of the yield that is plotted. The presence of these discrepancies indicates that the GDR strength function is more than just a simple Lorentzian. The next logical stage of analysis is to obtain a modified strength function without introducing any new fitting.
parameters. (The obvious temptation to use a double Lorentzian form could undoubtedly produce several better fits to the data but would not yield more meaningful physics.)

The low energy parts of statistical gamma ray spectra, such as those of Figure 1, are dominated by an exponential falloff which results from the exponential energy dependence of the level density. Because of this it is tempting to obtain a measure of the gamma ray strength function by dividing the experimental spectra by a factor \( \exp(-E_J/T) \), thus removing the level density dependence.\(^4\) Here \( T \) would represent an average characteristic temperature for the compound nucleus. As illustrated in Figure 4, this procedure yields misleading results. The short and long dashed lines in Figure 4a are exponential spectra characterized by temperatures of 1.95 MeV and 1.66 MeV, respectively. The ratio of the data to these lines is plotted in Figure 4b. If the region between 10 MeV and 20 MeV is supposed to reflect the gamma ray strength function, then radically different shapes can be obtained with only slight changes in the temperature parameter \( T \). This procedure cannot yield a measurement of either the GDR centroid or its width. Furthermore, since the level density and hence the nuclear temperature decreases through the various stages of the decay cascade, a unique value for \( T \) is rather badly determined. This is illustrated by the dotted curve in Figure 4a which results from an evaporation calculation assuming a constant energy independent matrix element for all gamma ray transitions. This curve merges with the solid curve below 8 MeV but bends up above 12 MeV, indicating that in a statistical description the higher energy gamma rays tend to come from regions of higher level density (higher \( T \)) where they can more effectively compete with particle evaporation.\(^4\)

We suggest that a more meaningful description of the gamma ray strength function is obtained by dividing the data not by an ad hoc exponential factor but by the calculated spectrum, assuming constant energy independent matrix elements (dotted curve in Figure 4a). The value of the matrix elements can be chosen to reproduce the low energy part of the observed spectrum. This divides out the effects of a changing level density in a consistent and unambiguous way, and should reveal the excited state and spin averaged strength function. The validity of this procedure in obtaining the gamma strength function can be checked by applying it to the spectrum calculated with a GDR of known parameters. This is shown in Figure 4d where the solid line is the ratio of the
FIGURE 4 (a) The $^{34}$S + $^{130}$Te data of Figure 1, together with two evaporation calculations (solid and dotted lines) and two lines of constant temperature (long and short dashed). (b) The ratio of the data to the lines of constant temperature. (c) The ratio of the data to the CASCADE calculation indicated by the dotted line in (a). (d) The ratio of the solid and dotted curves of (a), shown here as a solid line together with the shape of the strength function (open circles) that was used in the evaporation calculation represented by the solid curve in (a). See text for further details.
calculated spectra with a Lorentzian distribution (solid line in Figure 4a and Figure 1) and with constant matrix elements (dotted line in Figure 4a). For comparison the open circle curve in Figure 4d is just the gamma strength function that enters the calculation corresponding to the solid line in Figure 4a. Above 10 MeV, where this analysis is expected to work, the shape of the assumed strength function and of the ratio of spectra are indeed very similar.

This procedure is applied to the data in Figure 4c which above 10 MeV should then correspond to the exact shape of the excitation energy and spin averaged strength function that would perfectly reproduce the data. At first glance the shape is not the Lorentzian that might intuitively be expected. The most puzzling feature of the ratio spectrum of Figure 4c is its seemingly constant value at high energies. This could be produced by a GDR width which increases with excitation energy. In such a case transitions from the high gamma ray energy side of resonances would become more probable as the energies of the states upon which the GDRs are built increased. The increase in the density of such states at higher excitation energies would then tend to keep the excited state and spin averaged strength function from dropping. It must of course drop at some point, and it may indeed fall off at energies higher than those shown in Figure 4c, but as indicated by the error bars and the data of Figure 1 the cross sections are falling so rapidly with increasing energy that this will be very difficult to demonstrate experimentally. The above discussion stresses the importance of precisely measuring the shape of the gamma ray spectra at very high energy (in excess of 20 MeV) if one wants to reliably determine the properties of the strength function.

As mentioned previously, an increase in the width of GDRs at higher excitation energies has already been observed in proton capture to discrete states of light nuclei. In heavy nuclei, Draper et al. have recently suggested that an energy dependent GDR width might yield a better description of statistical gamma ray spectra emitted by fragments produced in deep inelastic reactions. It is certainly important to study this effect throughout a range of nuclei, preferably using fusion reactions where the product nuclei can be well defined. However, the statistical evaporation codes such as GROGI2 and CASCADE that have been used to analyze these heavy-ion reaction data do not readily allow the introduction of an excitation energy dependence into the GDR width.
A new or at least properly modified computer code is badly needed if real headway is to be made in this area.

It should be obvious from Figure 4 and the above discussions that beyond general characteristics remarkably little is really known about the origin of spectra such as those of Figure 1. The expected $A^{-1/3}$ dependence of the centroids of these GDRs has yet to be properly demonstrated over a wide mass range. In fact, there is no real proof that these high energy gamma ray transitions are actually dipole in nature. Attempts at studying angular distributions have been largely inconclusive. Because of the inherent averaging over many high spins in these reactions angular distributions are quite insensitive to the transition multipolarity, particularly since interference with even tiny $E2$ components could drastically alter their character. Nonetheless, assuming that the processes involved are really statistical it is very unlikely that the observed decays are anything but dipole, simply because the absolute magnitude of the gamma ray width ($\Gamma_\gamma$) contained in an $E1$ sum rule is at least 1000 times that contained in even an $E2$ sum rule.

The competition between gamma decay and neutron emission from heavy compound systems has been studied to investigate the statistical nature of these reactions. For example, the high energy gamma ray spectra shown in Figure 5 were collected in coincidence with low energy transitions in the indicated residual nuclei, these being identified by Ge(Li) detectors. The sum of all such contributions makes up the $^{34}S + ^{130}Te$ spectrum shown in Figure 1. At the bombarding energy chosen for these studies four-neutron evaporation dominates the reaction cross section, and indeed the majority of high energy gamma decays result in $^{160}Er$ as the final daughter nucleus. However, if the gamma ray yields associated with different final nuclei are divided by the partial fusion cross sections for producing these nuclei, then the resulting gamma decay probabilities are seen to be higher in the decay chains having fewer evaporated particles. This is evident in Figure 5 where the probability of gamma decay is increased by about a factor of 3 if $^{161}Er$ rather than $^{160}Er$ is the final residue. Qualitatively similar trends have been observed by the Heidelberg-crystal ball group. However, a quantitative description of such data with statistical evaporation calculations has not yet been undertaken. Nonetheless, some qualitative understanding of these trends is readily apparent. The slope of the low energy exponential (solid lines in Figure 5) is shallower in $^{161}Er$, indicating that the gamma
rays are coming from regions of higher temperature hence higher excitation energies. A higher excitation energy implies a higher level density which for roughly constant GDR sum rule strength will then give rise to more high energy gamma rays. If the decays are purely statistical the present data are consistent with the emission of these high energy gamma rays in the very early stage of the decay cascade, in direct competition with the particle evaporation. Some confirmation of this has been reported by Gaardhøje and collaborators.\textsuperscript{15} In this latter work spectra taken at different bombarding energies, which then correspond to different excitation energies in the compound system, were subtracted to obtain a measure of the gamma decay probability within a specific interval of compound nuclear excitation energy. Although this technique seems quite attractive, the strong exponential behavior of the spectra introduces large systematic uncertainties in the subtraction process and detailed studies will be necessary to assess the precision of this type of analysis.

If most of the high energy gamma rays do indeed come from the
regions of highest level density, then the largest single contribution to the high energy yield should come directly from the compound nucleus. This is indeed inherent in the evaporation calculations of Figure 1. The calculation for $^{34}\text{S} + ^{130}\text{Te}$ is shown again in Figure 6, together with the contributions obtained from the various stages of the decay cascade. Above $E_\gamma \approx 11$ MeV, the gamma decay probability increases as the number of evaporated particles decreases, and the total spectrum becomes dominated by radiative capture from the compound nucleus. This decomposition is extremely difficult to verify experimentally but nonetheless is consistent with the available data.

The decomposition shown in Figure 6 provides the strongest motivation for studying these reactions. Assuming statistical models are correct, the high energy parts of these gamma ray spectra are really probing the compound nucleus at its highest excitation energies. However, before this can be exploited the spin, energy and deformation dependences of GDRs built on excited states must be understood. A

![Figure 6](image_url)

**FIGURE 6** The decomposition of the CASCADE calculation for the $^{34}\text{S} + ^{130}\text{Te}$ system of Figure 1 into the contributions from radiative decays in $^{164}\text{Er}$, from decays in $^{163}\text{Er}$, . . . , from decays in $^{159}\text{Er}$. The curves are labelled on the left with the number of evaporated neutrons.
large and careful experimental effort is needed in this area. The discussion in this review is centered on reactions leading to lanthanide nuclei, partly because this is where most of the available data are concentrated and partly because the particle decay channels which compete with gamma emission are simple here (only neutron evaporation is involved). In reactions leading to lighter compound systems the overall enhancement in the high energy region of the gamma ray spectra is in fact larger than that seen in Figure 1. However, for these lighter systems neutron and charged particle decay channels now compete with the gamma rays. This makes the goal of separating the spin and energy dependences in the GDR strength function even more complicated. For example, Garman et al. have investigated the $^{12}\text{C} + ^{64}\text{Zn}$ and $^{18}\text{O} + ^{58}\text{Ni}$ reactions at bombarding energies designed to reach the same excitation energy in $^{76}\text{Kr}$, but with very different grazing angular momenta ($\sim 8\text{ f}$. and $11\text{ f}$, respectively). Although the absolute normalization of their data is not known, the shapes of the gamma ray spectra resulting from these two reactions are identical. This implies either that there is no spin dependence to the GDR shape, which is unlikely in the light of Figure 3, or that the dependence is somehow submerged in the complexity of the reaction.

The lightest system in which a statistical GDR-like enhancement to the gamma ray spectrum has been observed is $^{3}\text{He} + ^{25}\text{Mg}$ leading to $^{28}\text{Si}$, and indeed the enhancement is larger than in any of the other reactions discussed so far. Because the incident projectile is so light only very low spin states can be populated, and for bombarding energies not too far above the Coulomb barrier a decomposition similar to that of Figure 6 indicates that essentially all of the gamma rays above 13 MeV come directly from radiative capture into the compound nucleus. At this point these characteristics should probably be viewed as desirable attributes rather than limitations. With the spin degree of freedom removed and with the gamma-emitting stage of the decay cascade essentially fixed, it might be possible to isolate the excitation energy dependence of the GDR strength function. Nonetheless, an extensive systematic experimental program will be necessary before such an extracted energy dependence can be applied to heavier systems having spin as a degree of freedom. If we are to take a lesson from the more conventional photonuclear investigations of giant resonances built on nuclear ground states, then there is a great deal of work ahead for those who are attracted to this problem.
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