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E1 STRENGTH FUNCTION AT HIGH SPIN AND EXCITATION ENERGY

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Recently giant dipole resonance-like concentration of the dipole strength function in nuclei was observed at both high excitation energies and high spins. This observation raises the possibility of obtaining new information on the shape of rapidly rotating heated nuclei. Recent experimental results on this subject are reviewed.

The study of nuclei at high spin and excitation energy has been one of the most interesting field of nuclear physics in recent years particularly thanks to the availability of heavy-ion accelerators. The bulk of information on the properties of nuclei near the Yrast line originates from the spectroscopy of discrete states. However, as one wants to reach new domain of energy and spin, the complexity of the level schemes will compeil us to leave the more secure and precise world of discrete levels for the world of continuum spectra, average values and statistical properties. This transition will certainly be necessary if one wants to study nuclei in regions of spin and energy where gamma emission has to compete with particle evaporation or fission.

Along this line, the recent observation by a Berkeley group[1] that the statistical gamma-ray spectra following heavy-ion fusion reactions are not only reflecting the exponential behavior of the level density but contain structures at high gamma-ray energy that could be attributed to a giant resonance-like concentration of the gamma strength function is thus not only surprising but also very interesting.

It is well known that for statically deformed nuclei the giant dipole resonance (GDR) built on the ground state is splitted into two components which, in the hydrodynamical model of the GDR, correspond to the characteristic frequency of oscillation along the different axis of the spheroid. The energy difference between the two components is roughly proportional to the amplitude of the deformation whereas their respective intensity is related to its sign [2] . The observation of GDR-like structure in nuclei at very high spins or excitation energies raises the possibility of obtaining information on the shape of rapidly rotating heated nuclei in region not accessible to the spectroscopy of discrete states. This explains the great interest that this observation has generated.

Examples of the experimental observations are presented in fig. 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 [3].
In the energy range below 10 MeV, both spectra show the expected exponential fall-off characteristic of transitions deexciting statistically populated nuclear levels, with a constant matrix element. However, above 12 MeV there is a

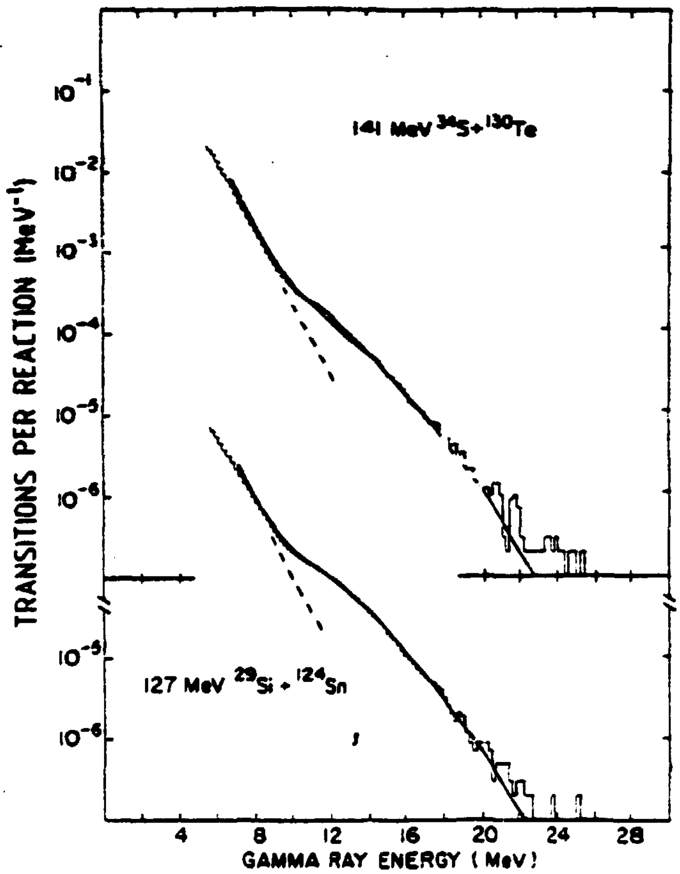

FIGURE 1 Statistical gamma-ray spectra from two heavy-ion reactions (ref.3). The dashed line extrapolates the low energy exponential behavior. The solid curves are the result of statistical model calculations assuming that each nuclear level has a giant dipole resonance associated with it.

considerable excess of gamma ray yield over the exponential (denoted by the dashed lines). The solid curve through the data of fig. 1 are calculated using a statistical evaporation code[4] assuming that all gamma ray transitions are E1 and that the dipole strength associated with each state follows a lorentzian distribution with shape parameters (resonance energy, width and amplitude) similar to the GDR built on the ground state of the compound nucleus. In this model, highly excited states, which are themselves giant dipole resonances built upon lower lying states, are statistically populated. The gamma decay from these highly excited levels appears enhanced above E_γ = 10 MeV simply because the gamma-ray strengths associated with these GDRs peak near a common energy namely the resonance energy. Similar observations have been made by many groups over a relatively broad mass range.[5-8]

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[9]. For the most part, this hypothesis has been tested only for low-lying states whose wave functions are very similar to that of the ground state [10]. Recently the gamma decay from proton capture reaction leading to particule-hole states in ^{28}Si of in fact relatively modest excitation energies (E^* = 5-15 MeV) and low spins has revealed GDR at energies nearly the same as that of the ground state GDR but with widths which increase drastically with excitation energy[11] reaching 12 MeV for $E^* > 10$ MeV. The detailed behavior of these widths is not yet understood but it tracks the increase complexity of the nuclear wave function with excitation energy. An extrapolation of that behavior to energies reached in heavy-ion fusion reactions would lead to so broad a distribution of the dipole strength function to be unrecognizable as a resonance. This explains that the results of ref. 1 were in part quite surprising.

Up to now the study of the emission of high energy gamma-rays from nuclei of high spin and excitation energy follows two main lines. The first one aims at determining the origin and nature of these transitions whereas the other approach assumes a GDR-like statistical decay and try to determine the shape of the gamma strength function (i.e. the resonance parameters) as well as its energy and/or spin dependence.

Attempts were made to establish the dipole nature of these transitions by measuring their anisotropy. In the two experiments where the anisotropy was measured relative to the beam axis, the results are very inconclusive and within the error isotropic distributions are observed[5,6] (fig.2).

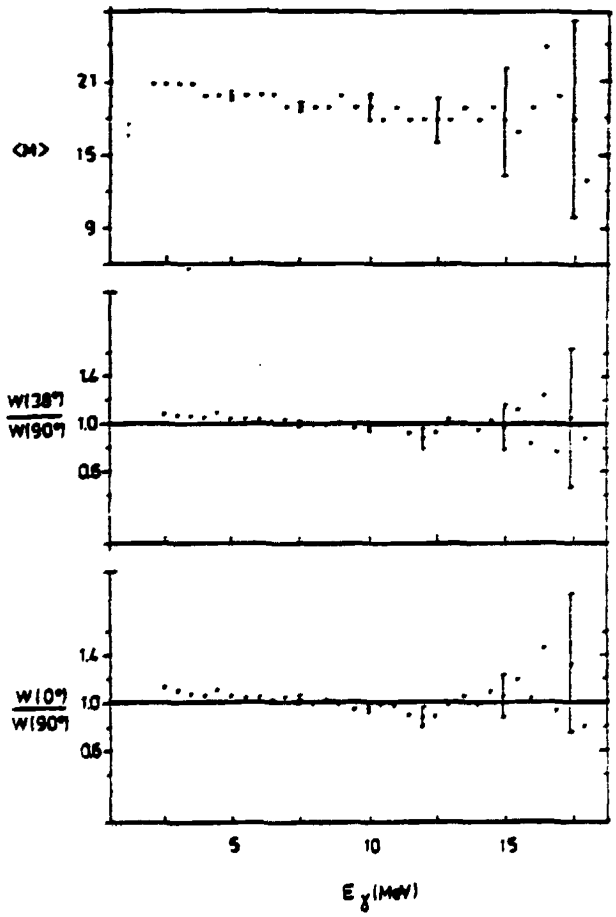

FIGURE 2 Multiplicity and anisotropy as a function of gamma-ray energy for the statistical gamma-rays from the reaction $^{120}Sn(^{28}Si,4n)^{144}Gd$ measured in delayed coincidence with the $I^{\pi} = 10^{+}$ isomer in ^{144}Gd (ref.5).

This result may not be very surprising since at high excitation energy, contrary to energy near the Yrast line, the level density does not vary rapidly with spin so stretched transitions which lead to strong anisotropy are only weakly favored. For example in ^{148}Gd statistical calculations predict an absolute anisotropy of less than 0.02 for purely dipole decay from any levels with $J \lesssim 25$ to states with $E^* \gtrsim 20$MeV. Non-zero anisotropy can however be present if the various K components of the gamma-strength function are well separated since the decay properties of these components could differ[5] resulting in stretched and unstretched transitions localized at different gamma-ray energies. Even in that case an appreciable attenuation of the anisotropy is expected due to the broad K distribution of the initial states [6] .

The new 4π NaI crystal ball spectrometers allow to measure the anisotropy relative to the direction of the nuclear spin determined for each event by the average direction of the collective transitions. This should result in enhanced anisotropies as compared to measurements relative to the beam axis. Preliminary results using the Heidelberg spectrometer seems to indicate non zero anisotropy[7] for high energy gamma rays from the fusion reaction ^{128}Te (^{34}S,xn)$^{162-x}$ Er. However a more recent analysis of their data give results more consistent with an isotropic distribution[12] in agreement with refs. 5 and 6.

Statistical models calculations predict that high energy gamma ray ($E_\gamma \gtrsim 10$ MeV) should originate from the region of highest level density or highest excitation energy. This is shown in fig. 3 where the calculated contributions to the gamma ray spectrum from the various steps of the decay cascade are presented for the reaction $^{34}S + ^{130}Te$. Assuming that the statistical model is correct, the high energy part of the spectrum is really probing the nucleus at its highest excitation energy. This decomposition which provides the strongest motivation for studying this type of reaction is, however rather difficult to test experimentally.

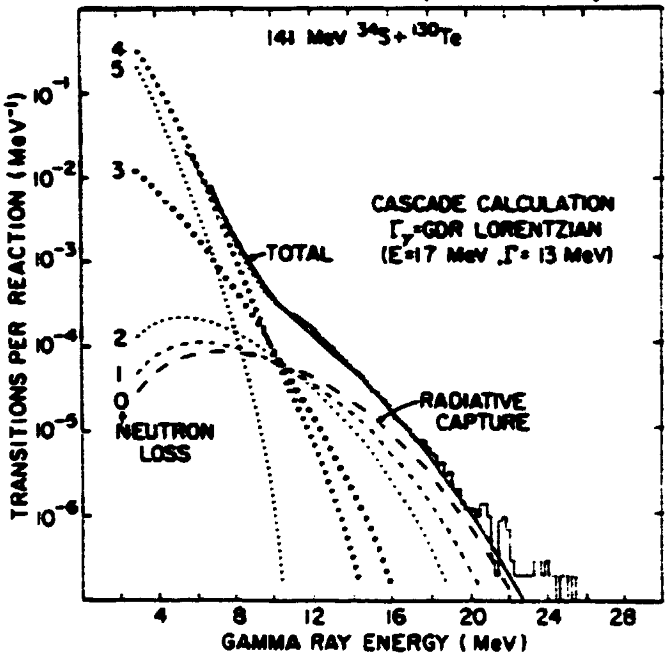

FIGURE 3 Decomposition of the statistical model calculations for the $^{34}S + ^{130}Te$ systems into the contributions from the successive decay steps.

Some confirmation of these predictions has been reported by Gaardhøje and collaborators[5]. Gamma-ray spectra from ^{166}Er and ^{165}Er compound nuclei produced at respective excitation energy of 62.7 and 50.9 MeV were compared. The excitation energy in ^{165}Er is lower by approximately the energy removed by the first neutron evaporated from ^{166}Er. Subtraction of both spectra should then yield the contribution from the first decay step. The resulting spectrum indicates that above E_{γ} = 10 MeV, roughly 30 to 40 % of the strength come directly from the compound system prior to particle decay, in qualitative agreement with the statistical model predictions (fig. 3). Although this technique seems quite attractive, the strong exponential behavior of the spectra introduces large systematic errors in the subtraction process and more detailed studies are necessary to assess the precision of this type of analysis.

The centroid of giant resonances is expected to follow roughly a $A^{-1/3}$ dependence. Such a behavior is observed for giant dipole resonances built on the ground state as well as for resonances of higher multipolarities[13]. Recent calculations have demonstrated that high spins and temperature do not modify appreciably the predicted position of the dipole resonance[14]. The first results from ref. 1 seem to indicate that the concentration of gamma strength follows the $A^{-1/3}$ mass dependence. However, the studied mass range was too small to ascertain this conclusion. More recent data covering a larger mass range ($46 \leq A \leq 164$) present a more puzzling picture[3] . The measured gamma-ray spectra are presented in fig. 4 together with the calculated spectra (solid curve) using a Lorentzian distribution for the dipole strength function with the parameters indicated in the figure. The centroids of the distributions are compared to that of the GDR built on the ground state in the upper part of fig. 5. The centroids of these average strength functions are strongly shifted in agreement with what was observed in other works but when viewed over a broad mass range these shifts are quite erratic and do not vary smoothly with the mass of the compound nucleus.

The most surprising result of the work of ref. 3 is that the average sum rule strengths extracted from the fits of

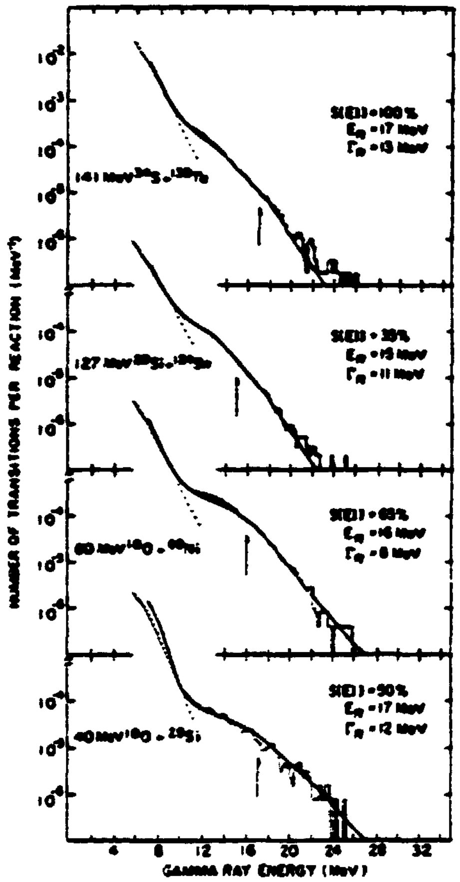

FIGURE 4 Comparison between statistical gamma-ray spectra following four fusion reactions and the spectra calculated assuming a Lorentzian gamma strength function (solid line) (ref.3).

fig. 4 follow the same trend as those of the corresponding ground state GDR observed in photo-absorption. This is shown at the bottom of fig. 5. The correspondence is not perfect but it seems that, whenever the ground state sum rule drops below 100 %, the strength value associated with the excited state giant resonance is also reduced. Because the strengths extracted from statistical model analysis represent a broad average over excitation energy and spin, the fact that they do track the observed ground state values suggests that the

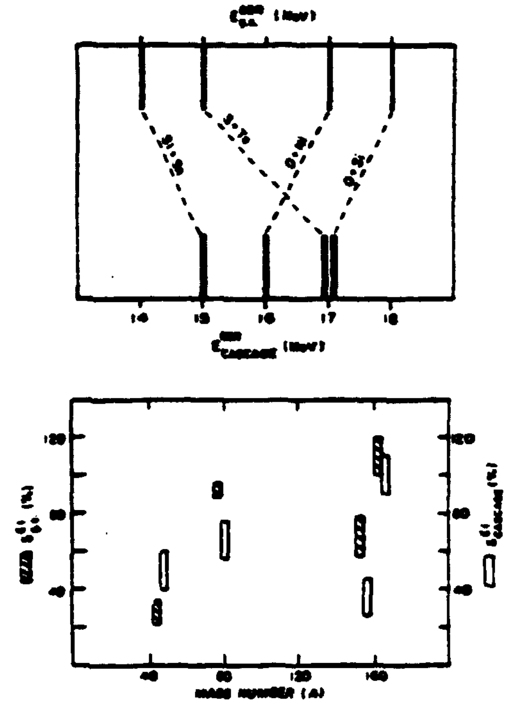

FIGURE 5 Comparison between the ground state giant dipole resonance parameters of the compound nuclei and that obtained from a fit to the statistical gamma ray spectra of fig.4.

specific fraction of E1 sum rule strength may be a general characteristic of all levels in a nucleus. This is quite unexpected since, at the high excitation energy probed in the present reactions ($E^* \approx$ 40-60 MeV), shell effects and pairing energy should become negligible for nucleons near the Fermi surface and all nuclei should more or less behave similarly.

Some attempts have been made to study the spin and excitation energy dependence of the gamma strength function. Spin selectivity has been achieved in partially exclusive experiments using sum spectrometers[1,6] or multiplicity filters[7] as gates. In all experiments, an overall enhancement of the high energy gamma-ray yield is observed for the lower spins (i.e. lower multiplicity or summed energy). A crude analysis of the data done by multiplying the spectra by an exponential factor exp (E_γ/T), which is aimed at removing the level density dependence, seems to indicate that the centroid of the strength function shifts to lower energy for the lower spins[6,7,12]. A more elaborate analysis of the data is, however, necessary to ascertain this conclusion since an exponential factor does not correspond to the level density dependence in the high gamma-ray energy region (see below) and furthermore an appreciable suppression of high energy gamma-rays is expected at high spins simply due to the lower effective excitation energy relative to the Yrast line. Only statistical model calculations could take these effects properly into account.

The excitation energy dependence of the gamma strength function was studied by Draper et al.[15] using deep inelastic products from the 1150 MeV ^{136}Xe + ^{181}Ta reaction. Eventhough the description of the data using statistical model calculations was not perfect, an increase in the width of the strength function with excitation energy was clearly observed. This is in qualitative agreement with the results of ref.11 on proton capture reaction in light nuclei. The advantage of deep inelastic reaction is to produce fragments with a complete range of excitation energies ; however, these fragments are distributed over a broad and not always easily determined range of spins, atomic numbers and masses which renders the comparison with statistical models rather difficult. More quantitative results will probably require the study of better defined systems as produced for example in fusion reactions.

Every group which have obtained the type of data presented in fig. 1 and 4 have tried to obtain the shape of the gamma strength functions or to determine the resonance parameters of these strength functions. Up to now, when compared, the results are at best inconclusive and often inconsistent. This is probably mainly due to the various ways to analyse the data as well as the various criteria used to determine a good fit to the data. Up to now, three main techniques have been used to obtain the resonance parameters, namely :

i) removal of a simple exponential dependence assumed to represent the level density dependence,[1,6,7]

ii) decomposition of the spectrum into a low excitation energy component plus a high energy contribution expected to represent the contribution from the region where gamma-ray emission competes with particle evaporation[5]

iii) comparison with the prediction of statistical models[3,8,15].

The low energy part of statistical gamma-ray spectra is dominated by an exponential fall-off which results mainly 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 such an exponential factor exp $(-E_{\gamma}/T)$ thus removing the level density dependence. Here, T should represent an average characteristic temperature. As illustrated in the second part of fig. 6 this procedure yields unreliable results.

Figure 6b presents the ratios of the data for the reaction $^{34}S + {}^{130}Te$ to two exponential spectra represented by the short- and long-dashed line in fig. 6a calculated using a temperature of 1.95 and 1.66 MeV respectively. These ratios which are expected to reflect the gamma strength function above E_γ = 10 MeV present radically different shapes with only slight change in the temperature parameter T. Since the level density and hence the nuclear temperature decreases through the various stages of the decay cascade a unique value of T is rather badly determined and this procedure cannot yield a measurement of either the centroid or the width of the strength function.

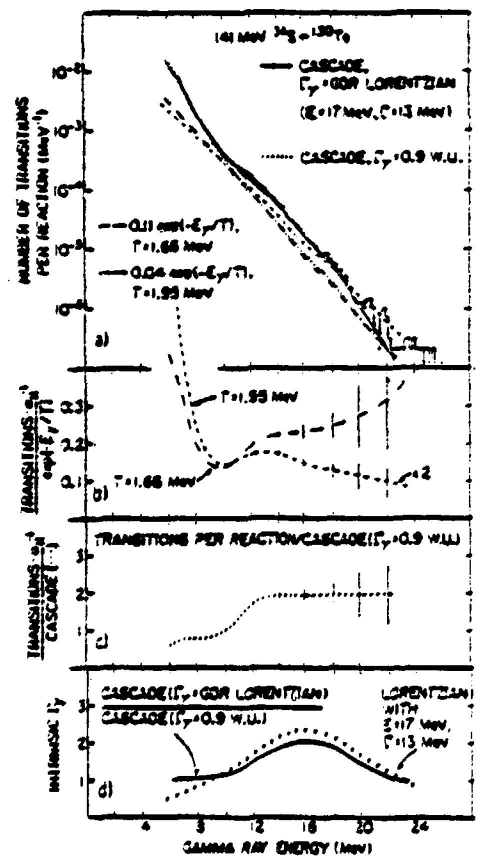

FIGURE 6 a) The statistical gamma ray spectrum for the reaction $^{34}S + ^{130}Te$ compared to two evaporation calculations (solid and dotted lines) and two spectra of constant temperature (long- and short-dashed). b) The ratio of the data to the lines of constant temperature. c) The ratio of the data to the dotted line in a). d) Comparison of the ratio of the solid and dotted curves in a) with the lorentzian shape of the strength function used to fit the data in a) (solid curve).

That the level density dependence of the statistical gamma-ray spectrum is not characterized by a single temperature is demonstrated by the dotted curve in fig. 6a which results from an evaporation calculation assuming a constant energy independent matrix element for all gamma-ray transitions. This spectrum merges below 8 MeV with the calculated spectrum assuming a GDR-like strength function (solid curve) but bends up above E = 12 MeV indicating that, in a statistical description, the higher energy gamma rays tend to come from regions of higher temperature or excitation energy where they can more effectively compete with particle evaporation, in agreement with the decomposition presented in fig. 3.

Comparison with statistical model calculations is certainly the most reliable way to determine the properties of the gamma strength function since only such calculations can take into account simultaneously the spin and excitation energy dependence of the competition between gamma decay and particle evaporation which, together with the form of the gamma strength function, will determine the shape of the statistical gamma ray spectrum. However, when a specific functional form is assumed for the gamma strength function such as a lorentzian (fig. 4 and solid line in fig. 6a), the extracted parameters of this function depend often on the criteria which are used to define an acceptable fit of the calculation to the data and furthermore these parameters (width, resonance energy and amplitude) are far from independent in obtaining an acceptable fit to the data.

A more consistent and reliable procedure to obtain the gamma strength function from the measured statistical gamma-ray spectra has certainly to be developped before a useful comparison of the results obtained by the different groups can be done. An analysis which would determine the shape of the gamma-strength function without relying on a specific functional form (or parameters) but which would still treat properly the statistical competition between gamma decay and particle evaporation would certainly be desirable. A first approach in this direction is possible if instead of dividing the data by an ad-hoc exponential factor, the data are divided by the calculated spectrum assuming constant energy independent matrix elements (dotted curve in fig. 6a). 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 for gamma ray energy above 10 MeV is shown in fig. 6d where the ratio of the spectra calculated assuming a lorentzian strength distribution (solid line in fig. 6a) to the spectra calculated assuming a constant matrix element (dotted curve in fig. 6a) is compared to the lorentzian strength function. Above 10 MeV where such an analysis is expected to work, the shape of the assumed strength function and the ratio of the spectra are indeed very similar.

This procedure is applied to the data for the system $^{34}S + ^{130}Te$ in fig. 6c. The first impression is that the ratio is not a lorentzian as was assumed. Furthermore the strength function does not seem to drop at the highest energy. However, as indicated by the error bars and the data in fig. 6a, the cross section is falling very rapidly with increasing gamma ray energy and it may be very difficult to determine precisely this fall-off. Fig. 6c stresses the importance of measuring precisely the shape of the gamma-ray spectrum at very high energy (in excess of 20 MeV) if one wants to determine reliably the properties of the strength function.

The data reviewed above clearly demonstrate that a concentration of the gamma-strength function is observed in nuclei even at the high excitation energies and spins reached in heavy-ion induced reactions. There seems to be a broadening of the strength function with excitation energy which could reflect the increasing complexity of the states at these energies. May be due to this increasing width or to the broad average on spin and temperature inherent to spectra from heavy-ion induced fusion reaction, no fine structure or splitting of the strength function has been observed. More exclusive data which could isolate the contribution from a small region of spin and excitation energy are probably needed to reveal any possible structure in the strength function. The new 4π NaI crystal ball spectrometers are certainly the best tool presently available to undertake such studies.

The study of giant dipole resonance at high spin and excitation energy is a new and exciting subject. An extensive systematic experimental program as well as a better understanding on how to obtain the gamma-strength function from the measured data are, however, needed before we can use such resonances to tell us something new about the behavior of rapidly rotating treated nuclei.

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