GIANT RESONANCES IN HOT NUCLEI*,**

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The γ decay of the Giant Dipole Resonances, GDR, coupled to excited states in hot nuclei is discussed. We concentrate on the evolution of the experimental methods tending towards larger selectivity, *i.e.* determination of the quantities measured in a specific region of excitation energy and angular momentum of a particular, identified nucleus. We present also some representative examples of the studies in which GDR was used as a tool to obtain information about hot, fast rotating nuclei. The first experiments attempting to study the dilepton decay of the Giant Monopole Resonance in hot nuclei are briefly discussed.

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1. Introduction

Giant Resonances, GR, are the high frequency collective modes of nuclear excitations. According to the Brink–Axell hypothesis [1] a GR may

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be built on every nuclear state. Thus one may study *e.g.* the GR's coupled to highly excited states in hot nuclei, populated in a statistical way by the heavy-ion fusion reactions. The electromagnetic decay of such coupled GR's competes weakly with the dominant particle decay (on the level of 10^{-3}). The decay occurs throughout the evaporation cascade, although it is most likely to take place at the first few steps of the cascade. The particle evaporation and the competing high energy gamma decay proceed until the residual nucleus is populated in a vicinity of the yrast line. At this point the nucleus is left with an intrinsic excitation energy of 8–9 MeV and, on the average, with a large value of the angular momentum. The latter is carried away mainly by the emission of low-energy γ-rays.

In spite of the γ-branch of the GDR decay being so weak it has become during the last 12 years the main tool for studying GDR in hot nuclei. In contrast, the GR's of other multipolarities coupled to excited states are much more difficult to study. The Giant Monopole Resonances, GMR , cannot decay by the single photon emission and the only observable is the 10^{-4} times weaker dilepton decay channel. The γ-decay of the Giant Quadrupole Resonances, Isoscalar as well as Isovector, is much weaker than that of the GDR, so that the unambiguous observation is very difficult.

The present paper concentrates on the most important results related to the studies of the GR in hot nuclei and obtained by three groups: the NPL Seattle, the NBI Copenhagen–Milano University collaboration, and the KVI Groningen. We shall discuss the evolution of experimental techniques for the studies of GDR in hot nuclei on the one hand and the information on the nuclear properties at high temperatures and angular momenta obtained from such studies on the other. We will also briefly describe the first attempts to study the GMR in hot nuclei. Finally, some expectations concerning these studies in the near future will be presented.

2. GDR studies

2.1. Inclusive experiments

In order to present an evolution of the experimental techniques for the GDR studies we have to start from inclusive experiments. Typically, the γ-rays from the decay of highly excited compound nuclei formed in heavy-ion fusion reactions were detected in such experiments with a large NaI(Tl) crystal surrounded by an active plastic anticoincidence shield and a passive lead shield in order to reject cosmic ray events and low-energy γ-ray background. Pulsed beams and time-of-flight techniques were used to separate prompt γ-rays produced in the target from neutron induced events. The measured γ-ray spectrum was then a sum of the γ-ray spectra from the decay of the initial compound nucleus and the daughter nuclei populated by particle emission. The GDR parameters: the strength S, the resonance energy $E_{\rm GDR}$ and the width Γ were extracted from the fits of the statistical model calculations to the data. The parameters obtained in this way are the averages over the decay steps, the spin and the temperature of the decaying nuclei. The experiments were performed at different projectile energies populating highly excited states of the same compound nucleus.

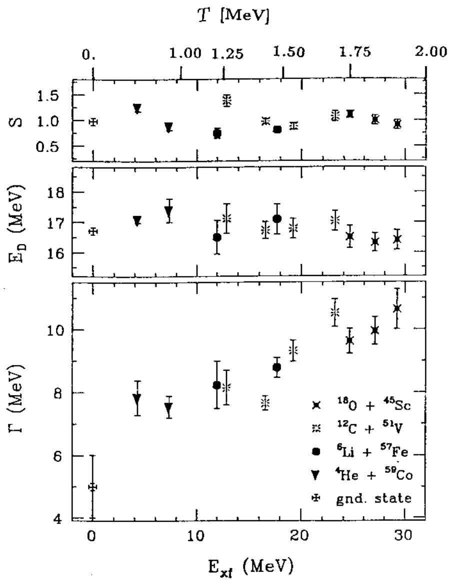

Fig. 1. GDR parameters of ^{63}Cu as functions of final excitation energy above the yrast line, and nuclear temperature. (From Ref. [3].)

Studies of this kind have been done by the Gaardhøje group in Copenhagen [2] and by the Snover group in Seattle [3]. They indicated, among other things, that there is a strong dependence of the GDR width on the excitation energy E_x, while the resonance energy and strength seem to be constant over a broad range of E_x (Fig. 1). The observed dependence of the width on E_x includes both the temperature and the spin dependence. A conclusion from those experiments was that the GDR width depends strongly on the angular momentum as a result of large spin-driven deformations. However, the dependence on the temperature was also included in those data. In one Seattle experiment [4] nuclei with $A \approx 40$ have been populated at the average effective temperature being nearly constant, $T = 1.7$ - 1.8 MeV. Strong increase of the GDR width, by 3 MeV, with an average spin increasing from 8 to 18.5 $\hbar$ was observed. The measured $a_2(E_\gamma)$ coefficient of angular distribution also suggested large spin-driven deformations.

2.2. Coincidence experiments — multiplicity filter

It was soon realized that in order to explain the behaviour of the GDR width the temperature and spin dependence of the GDR parameters have to be disentangled. This has been achieved by coincidence measurements with multiplicity filters consisting of many small size detectors with high efficiency for detecting low-energy γ-rays. The coincidence fold gives information on the initial angular momentum of the compound nucleus. A very efficient detection system was built at the NBI in Copenhagen [5]. High-energy γ-rays are measured in a detector array HECTOR consisting of 8 large volume BaF_2 scintillators placed at different angles with respect to the beam direction. The associated multiplicity filter HELENA consists of 38 smaller BaF_2 detectors and has the total efficiency of the order of 70 %. This allows to select with quite a good precision ($\sim$ 20%) the angular momentum of the nucleus emitting the γ-ray. Still, the high-energy γ-rays measured in such experiments originate from all the daughter nuclei produced during the evaporation cascade.

2.3. GDR width — quantal and thermal fluctuations

The coincidence method with multiplicity filters has been applied to the detailed studies of the GDR width in hot nuclei [6, 7]. Why studying the width is so important? It is really the total GDR width which is affected by the couplings of GR to small amplitude quantal fluctuations and to large amplitude fluctuations of the nuclear surface. Thus studying the behaviour of the GDR width as a function of temperature and spin one may get information about the deformation of the nucleus and about the thermal and the quantal fluctuations.

The GR is described microscopically as a correlated particle-hole excitation. The coupling of the GR to 2p-2h states produces a fragmentation of the strength and the resulting width is the spreading width. The coupling to progresively more complicated states lying at the same energy smoothes each fragmented component giving as a result the damping width [8]. This is the so called collisional damping and it is connected with the coupling of the giant modes to the small amplitude quantal fluctuations of the nuclear surface. The associated damping width (*i.e.* the intrinsic GDR width), does not differ substantially from the spreading width, which has been predicted not to change when the nuclear temperature increases [6].

Another mechanism which is important for the GDR width is the coupling to large amplitude fluctuations of the nuclear surface. It is well known that the GDR strength splits into a few components in deformed nuclei. This phenomenon is connected with the relation of the GDR resonance energy to the size of the nucleus in the direction of vibrations. This kind of damping is expected to be sensitive to the excitation energy of the compound system. At finite temperature, the nucleus will undergo thermal shape fluctuations probing an ensemble of shapes with the probability given by the Boltzman factor [9, 10]. Thus the GDR width observed at a given temperature and spin is a result of averaging of the GDR vibrations over the whole ensemble of deformed shapes. As the temperature increases, shapes far from the equilibrium configuration become more probable. The resulting spread in E_{GDR} will increase giving raise to a larger width. As the angular momentum increases the Coriolis and centrifugal forces will tend to increase the deformation of the nucleus, which will also result in an increase of the total width.

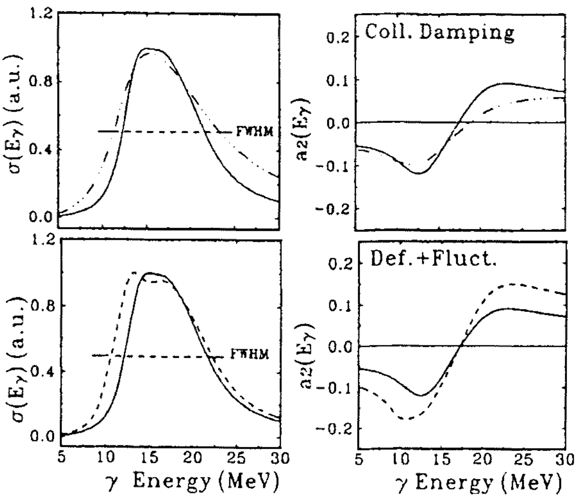

Fig. 2. GDR strength function and $a_2(E_\gamma)$ coefficient calculated within the thermal fluctuation model. The calculations shown in the top panel use intrinsic GDR width $\Gamma_0 = 5$ MeV (solid line) and $\Gamma_0 = 6$ MeV (dashed line) and the rotational frequency $\omega = 1.0$ MeV. The calculations in the bottom panel both use $\Gamma_0 = 5$ MeV and $\omega =$ 1.0 MeV (solid line) or $\omega = 1.25$ MeV (dashed line). (From Ref. [6].)

Recently the Milano–Copenhagen–Cracow group has studied the shape of the resonance strength function $\sigma_{\mathrm{abs}}(E_\gamma)$ and the angular distribution $a_2(E_\gamma)$ coefficient for ^{110,109}Sn nuclei in narrow intervals of spin I. As pointed out by Bracco and collaborators [6] it is very important to study these two quantities simultaneously because the broadening of the GDR width can be due either to an increase of the collisional damping width or to an increase of the nuclear deformation resulting from the fast rotation or from thermal fluctuations. As shown by the calculations within the thermal fluctuation model of shape and orientation (Fig. 2) the increase of the Γ_{GDR} by 1 MeV due to an increase of the collisional damping broadens the resonance strength function but does not affect the $a_2(E_\gamma)$ coefficient. If, however, the $\Gamma_{\rm GDR}$ increase is due to the increase of deformation of the nucleus induced by the rotational frequency, then the anisotropy of the $a_2(E_\gamma)$ connected with the separation of the GDR components increases. The orientation fluctuations, on the other hand, do not affect the GDR width but they will decrease the anisotropy of a_2.

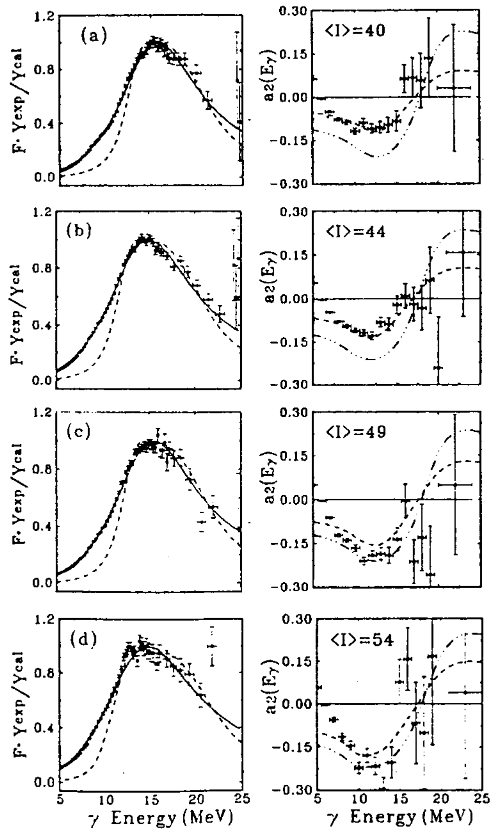

Fig. 3. Measured GDR strength functions and $a_2(E_\gamma)$ coefficient for ^{110,109}Sn for four mean spin values $\langle I\rangle$. The dashed lines are calculations within the model of thermal fluctuations of shape and orientation. The dot-dashed lines include only shape fluctuations. (From Ref. [6].)

Hot and rotating ^{110,109}Sn nuclei were formed [6] at nearly fixed temperature $T \approx$ 1.6–2.0 MeV. The γ-spectra have been sorted gating on different folds and four spin intervals were chosen corresponding to the mean spin $\langle I\rangle = 40, 44, 49$ and 54 $\hbar$. For the spin increase from 40 to 54 $\hbar$ the increase of the $\Gamma_{\rm GDR}$ by 2 MeV as well as an increase of the anisotropy of $a_2(E_\gamma)$ was observed (Fig. 3). It was then concluded that in the case studied the increase of the $\Gamma_{\rm GDR}$ is not due to the damping width but it is caused mainly by the coupling of the dipole vibrations to deformations which are larger at higher angular momenta. This was confirmed by the calculations within the thermal fluctuation model of shape and orientation.

The Sn nuclei are rather soft. Another example studied by the same group [7] concerned a more stiff nucleus, ^{176}W. In this case the effect of collisional damping should be enhanced because the shape effects are expected to be reduced. The Γ_{GDR} studied for $T \approx 1.35-1.49$ MeV and $\langle I \rangle = 36-55$ $\hbar$ has been found not to change while the anisotropy of $a_2(E_\gamma)$ has been found to increase with the increasing $\langle I \rangle$. Comparing these results with different options in thermal shape and orientation fluctuation calculations the authors concluded that the damping width does not change with increasing spin and that the orientation fluctuations are more important at lower spin values.

The main conclusion from this kind of studies is that the intrinsic GDR width is not affected by the spin and the temperature and that it is equal to the intrinsic width at the ground state. Thus may be *the Brink–Axell hypothesis* should finally be called *the Brink–Axell rule.*

The increase of the total GDR width at high rotation (corresponding in nuclei with $A \approx 100-200$ to $I \approx 30$ $\hbar$ and higher) is connected with the nuclear deformation and softness of the nucleus. At low rotations ($I < 30$ $\hbar$ for nuclei with $A \approx 100-200$) the influence of spin is not important and the increase of the total GDR width is mainly connected with the thermal shape fluctuations. Note that in lighter nuclei a "high rotation" corresponds to spins lower than 30 $\hbar$.

2.4. Nuclear shape and deformation

Since the behaviour of the GDR width seems to be well understood, a similar experimental method, which determines the $\sigma_{\mathrm{abs}}(E_\gamma)$ and $a_2(E_\gamma)$, may be used to study the angular momentum induced shape changes of hot, fast rotating nuclei. This kind of studies has been performed for several nuclei, ranging from light through heavy. The shape changes from spherical to oblate and from prolate to oblate have been found (*e.g.* [11, 12]). Most interesting in this respect are the shape changes of light and medium mass nuclei for which at very high rotation the equilibrium shape should undergo a shape transition from oblate to triaxial (approximately prolate) with a superdeformed major-to minor axis ratio of 2:1 or greater. To search for this effect two experiments have been performed at the NPL Seattle: an inclusive measurement [13], ^{18}O + ^{27}Al$- >^{45}$Sc, and a coincidence one [14] with a multiplicity filter, ^{32}S + ^{27}Al$- >^{59}$Cu. The calculated fusion cross sections for both reactions (in the case of ^{59}Cu also the measured one) imply the spin distribution which extends significantly beyond the critical angular momentum l_I predicted for the oblate-triaxial transition. The γ-ray spectra and angular distributions for 5 angles have been measured with a large $NaI(Tl)$ detector and for the ^{59}Cu also with the Seattle multiplicity filter. The statistical model fits to the γ-ray spectra revealed broad GDR strength functions $\sigma_{abs}(E_\gamma)$ implying a presence of large deformations in the ensemble of decaying states (Fig. 4). Thermal fluctuation calculations in which the GDR is averaged over a distribution of deformations determined from rotating liquid drop model potential energy surfaces reproduce well the measured GDR strength functions.

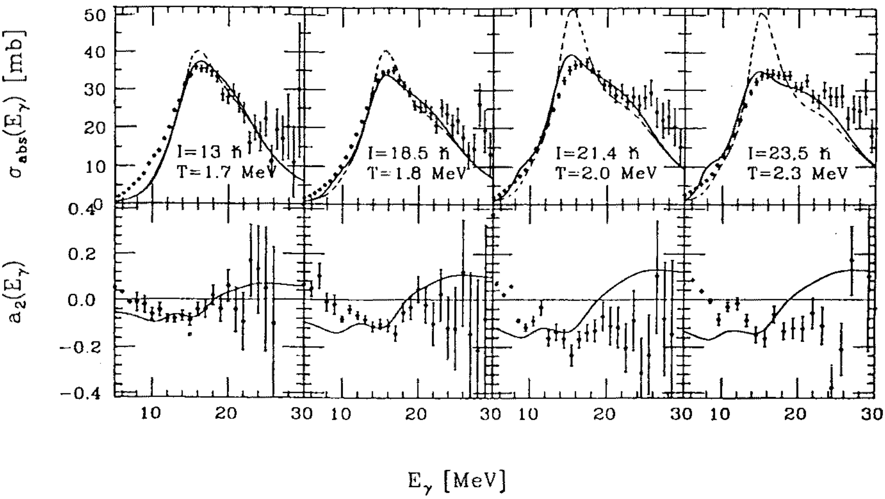

Fig. 4. Measured GDR strength functions and $a_2(E_\gamma)$ coefficient for ^{45}Sc (inclusive experiment). Solid lines are thermal fluctuation calculations with the RLDM PES. Dashed lines: thermal fluctuation calculations with the phase transition removed. (From Ref. [13].)

The calculations predict a substantial softenning of the potential energy surface (PES) at high spin, in addition to the equilibrium oblate-to-triaxial shape change. The experimental results were found to be sensitive mostly to this softenning. The calculations failed to reproduce the experimental cross sections at high spin when the oblate-to-triaxial shape transition and the associated softness in the PES have been removed [13, 14]. This confirms that the observed broadenning of the GDR strength function is mostly due to the spin-induced deformations. The calculated $a_2(E_\gamma)$ agree with the data only on the low energy side of the resonance. At energies above the GDR centroid there are discrepancies observed for high projectile energies. This effect, observed previously for the ^{18}O + ^{27}Al reaction, is seen also in the coincidence experiments for the ^{32}S + ^{27}Al reaction (Seattle) as well as for ^{18}O + ^{28}Si (Copenhagen, [15]).

2.5. The differential method

The subsequent step in the experimental procedures, which has been proposed by Gaardhøje and collaborators [16] and later improved by the Copenhagen–Milano–Cracow group [12], is the differential method. The idea is that two compound nuclei, with mass numbers differing by one neutron, are produced in two different heavy-ion fusion reactions. The projectile energies are chosen so that the excitation energies of the compound nuclei formed in the two reactions differ by the average energy removed by the first evaporated particle. The γ-ray spectrum measured for the reaction at lower excitation energy is then subtracted from the other one after normalisation to the same number of high fold triggers.The latter are assumed to be equal to the number of fusion reactions (Fig. 5). Assuming that the

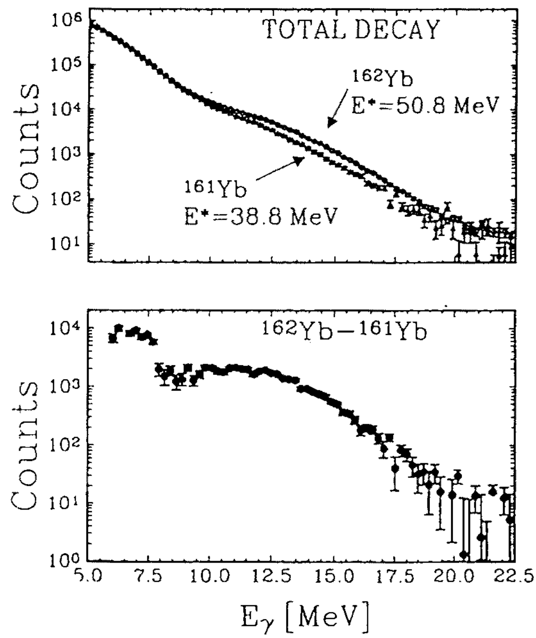

Fig. 5. Top: Measured high-energy γ-ray spectra from ^{162}Yb and ^{161}Yb. Bottom: The difference of the two spectra contains most of the GDR γ-rays emitted directly from the ^{162}Yb compound nucleus. (From Ref. [12].)

decaying nuclei are in the thermal equilibrium one may claim that the difference spectrum contains the first chance γ-rays from the heavier compound nucleus. This method has been applied to ^{162}Yb [12]. An analysis of the angular distribution for the difference spectrum permitted the authors [13] to decompose this spectrum into components related to the GDR vibrations parallel and perpendicular to the spin axis and to deduce information on the deformation of the nuclei at a well defined temperature. Thus *e.g.* a large admixture of oblate shapes has been found at T around 1.3 MeV.

2.6. Coincidence experiments - triggering on isomeric decay

In order to obtain higher selectivity in the GDR experiment another interesting method has been applied at KVI Groningen. In systematic studies of hot, fast rotating light Dy isotopes the number of decay channels was limited by triggering on specific final nuclei [17, 18]. Here the existence of long-lived isomeric states in ^{149}Dy ($I^\pi = \frac{47}{2}^+$, $T_{1/2} = 28$ ns), ^{151}Dy ($I^\pi = \frac{49}{2}^+$, $T_{1/2} = 13$ ns and $I^\pi = \frac{41}{2}^+$, $T_{1/2} = 6$ ns) and ^{152}Dy ($I^\pi = 17^+$, $T_{1/2} = 60$ ns) has been made use of. The compound nuclei of ^{156}Dy were formed in the ^{40}Ar + ^{116}Cd fusion reaction at $E_{\rm lab} = 200$ MeV [18]. The recoil nuclei were stopped in a catcher foil 25 cm from the target. High-energy γ -rays were detected in a large NaI(Tl) spectrometer. To detect the delayed γ-rays in ^{149}Dy, ^{151}Dy and ^{152}Dy, the catcher foil was surrounded by a ring of 8 NaI(Tl) detectors and one additional NaI(Tl)

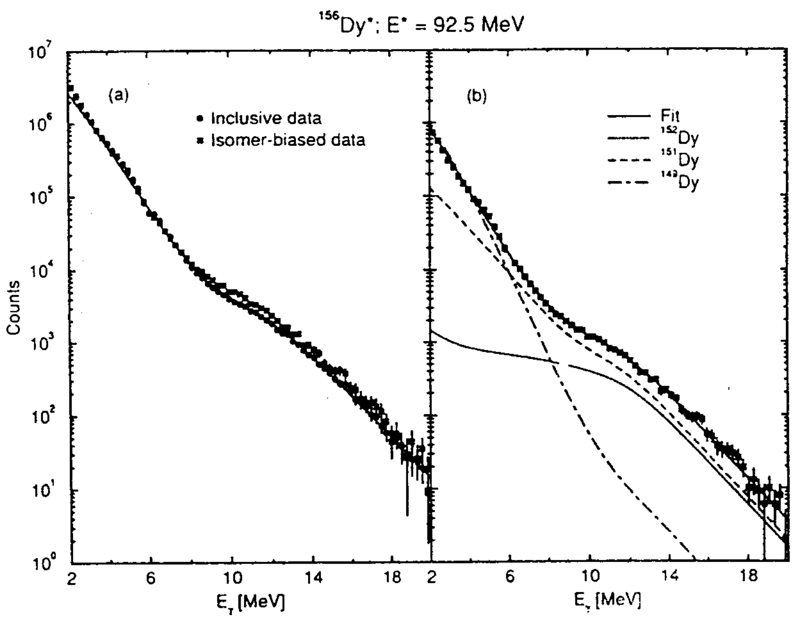

Fig. 6. a) Measured high-energy γ-ray spectra from ^{156}Dy from inclusive experiment and in coincidence with isomeric decay (shown also in (b)) normalized at low E_γ. b) Decomposition of the fitted spectrum into contributions of γ-ray yield in coincidence with isomeric decay occuring in ^{149,151,152}Dy nuclei. (From Ref. [18].)

positioned at 0^o and looking towards the target. A Compton suppressed Ge telescope was detecting the low-energy γ-rays. A multiplicity filter was used. The projectile energy has been chosen so that on the average 6 neutrons were evaporated in the decay paths in which no high-energy γ-ray was emitted. These decay paths thus ended mostly in ^{150}Dy, which is the only Dy isotope produced which does not have an isomer. If, on the other hand, a high-energy γ-ray was emitted, the number of evaporated neutrons was decreased to 4 or 5, depending on the angular momentum of the initial compound nucleus. In this case the final nuclei were ^{152}Dy or ^{151}Dy, which have isomers.

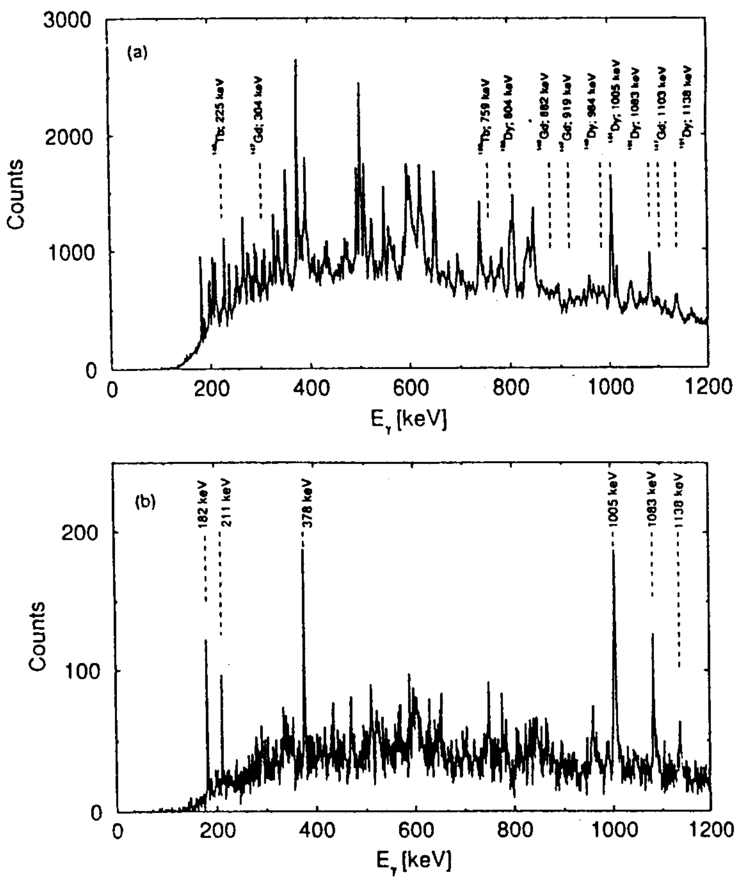

Fig. 7. Low-energy γ-ray spectra as measured with *Ge* telescope from ^{156}Dy; from a) inclusive experiment, b) in coincidence with a delayed γ-ray transition. (From Ref. [18].)

In Fig. 6a the total inclusive high-energy γ-ray spectrum measured with a large NaI(Tl) spectrometer is compared with the spectrum obtained with a condition that a γ-ray from the isomeric decay is detected in any of the NaI(Tl) detectors viewing the catcher foil. Both spectra are normalized in the energy range $E_\gamma = 2-5$ MeV. The relative yield of high-energy γ-rays ($E_\gamma \geq 8$ MeV) compared to the low-energy yield is larger in the spectrum triggered on the isomeric decay. The low-energy yield is strongly suppressed since only selected decay paths are included, whereas most of the yield of high-energy γ-rays originates from nuclei populated in these pathways. In Fig. 6b the decomposition into the contributions of γ-ray yield in coincidence with isomeric decay occuring in ^{149,151,152}Dy nuclei is shown. To check the selectivity obtained by triggering on γ-rays from isomeric decay, the discrete γ-ray spectrum measured with the *Ge* detector (Fig. 7a) has been analysed with a coincidence condition with delayed γ-rays the same way as the high-energy spectrum taken with a large NaI(Tl). Strong ^{151}Dy lines seen in the resulting spectrum (Fig. 7b) indicate that an isomeric decay is indeed an effective filter to select events corresponding to specific final nuclei.

The data for $^{156}Dy^*$ were also analysed as a function of the coincidence fold distribution [19]. Three regions have been selected with the average angular momentum 32, 46 and 62 $\hbar$. The GDR parameters extracted from the fits of the statistical model CASCADE calculations to the data for different spin windows suggest that the average nuclear deformation of ^{156}Dy increases with increasing angular momentum and temperature. The sign of the deformation, however, could not be determined unambiguously.

The γ-ray spectrum gated by an isomeric decay cannot be compared directly with statistical model calculations carried out with the CASCADE code. This is because the high-energy γ-rays can be emitted at each decay step in many possible decay paths and the code does not permit to select the pathways ending at the isomer. Thus an approximated method of CASCADE calculations was proposed [18]. In Fig. 8 the results of the fits to the inclusive spectrum and the spectrum triggered by an isomeric decay of ^{156}Dy are shown. The deformation parameter β deduced from the inclusive spectrum and from the spectra corresponding to the two highest angular-momentum selected windows are very close in value. In neither case, however, could the sign of β be determined. From the spectrum triggered on isomeric decay $\beta = -0.29$ for ^{156}Dy at $T \approx 1.6-1.9$ MeV and $I \approx 30-65\ \hbar$. Here the sign was determined indicating a shape transition from prolate to oblate. Similar studies have been also performed for ^{154}Dy nuclei at $T \approx 1.35-1.55$ MeV and $I \approx 30-50\ \hbar$ [17]. Here the low-energy GDR component was found to be very narrow (Fig. 9) and $|\beta| \approx 0.4-0.5$ suggesting superdeformation, with the sign of the deformation parameter undetermined.

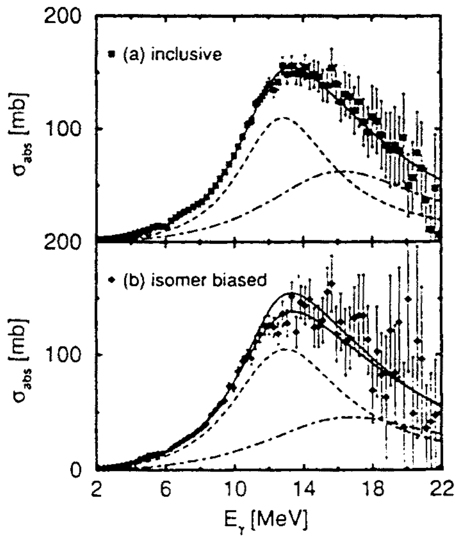

Fig. 8. Measured GDR strength functions for ^{156}Dy from a) inclusive experiment and b) in coincidence with isomeric decay. Decomposition into two components is also shown. Bottom curve in (b) is the fit shown in (a). (From Ref. [18].)

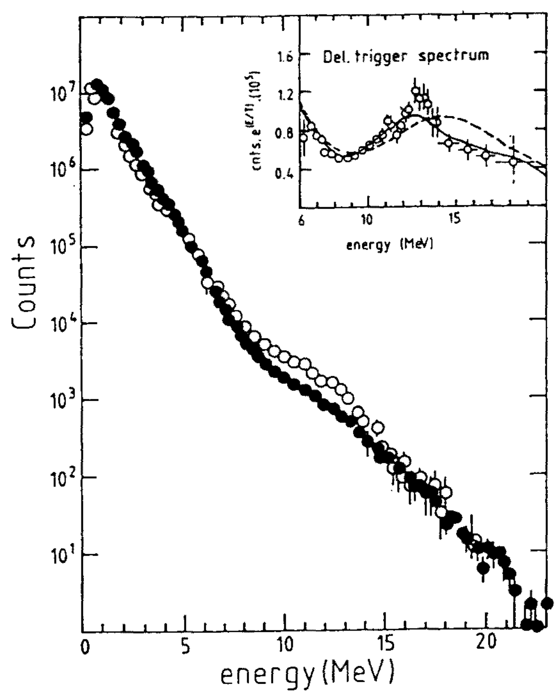

Fig. 9. a) Measured high-energy γ-ray spectra from ^{154}Dy from inclusive experiment and in coincidence with isomeric decay. (From Ref. [17].)

2.7. Coincidence experiments - with fission fragments

Another method for choosing a specific decay channel consists in measuring the GDR photons in coincidence with fission fragments. Fission becomes an effective mode of decay of the fused system at high angular momenta because of the lowering of the fission barrier due to fast rotation. This makes it possible to use fission as a highly sensitive trigger to select the highest angular momenta the nucleus can sustain.

Another application of the fission trigger is to study properties of very heavy nuclei. It is already known from the measurements of the prescission and postscission neutrons [20] that fission of a compound nucleus is a relatively slow process. The γ decay of the GDR excited in a heavy compound system can therefore occur before the system fissions.

This possibility of observing the GDR decay prior to fission has been used by the Copenhagen-Milano-Cracow group [21] to study properties of the nuclei with $Z \approx 108$. The experimental set-up consisted of the HECTOR array of large BaF_2 to measure the high-energy γ-rays, of the part of HELENA multiplicity filter and 4 PPAC (Parallel Plate Avalanche Counters) detectors, where the fission fragments were detected. An event was accepted when both fission fragments were detected in the two oposite PPAC detectors.

The pre-fission γ-ray spectrum has to be distinguished from that emitted from the hot fission fragments. The GDR energy is proportional to $A^{-\frac{1}{3}}$; thus for nuclei with $A = 272$ and $A = 136$, for symmetric fission products, the difference in $E_{\rm GDR}$ is only 3–4 MeV. Thus a special method was proposed [21] based on the differential method discussed earlier and an assumption that fission is slow and occurs only when the system is cold enough. This allows to localize the excitation energy E_f at which the fission starts.

Two reactions with the same projectile and target nuclei have been studied at different projectile energies. The ^{272}Hs nuclei at $E_x = 380$ MeV were populated. The emission of high-energy γ-rays is possible in a competition with neutron and charged particle emission until the excitation energy comes down to E_f. Then the fission starts and two hot fission fragments are formed which could also evaporate particle and γ-rays from the GDR decay. In the second reaction the initial excitation energy $E_x = 230$ MeV was still higher than E_f. Thus the situation was similar but the excitation energy E_f was here reached after smaller number of decay steps. The total γ-ray spectra from both reactions have been subtracted from each other after proper normalization. The difference spectrum should contain only the high-energy γ-rays emitted before fission by the hotter compound system (Fig. 10). In order to localize the E_f an additional measurement has also been performed for E_x = 105 MeV and in the difference spectrum both prefission and post fission components were found which suggested that 105< E_f <230.

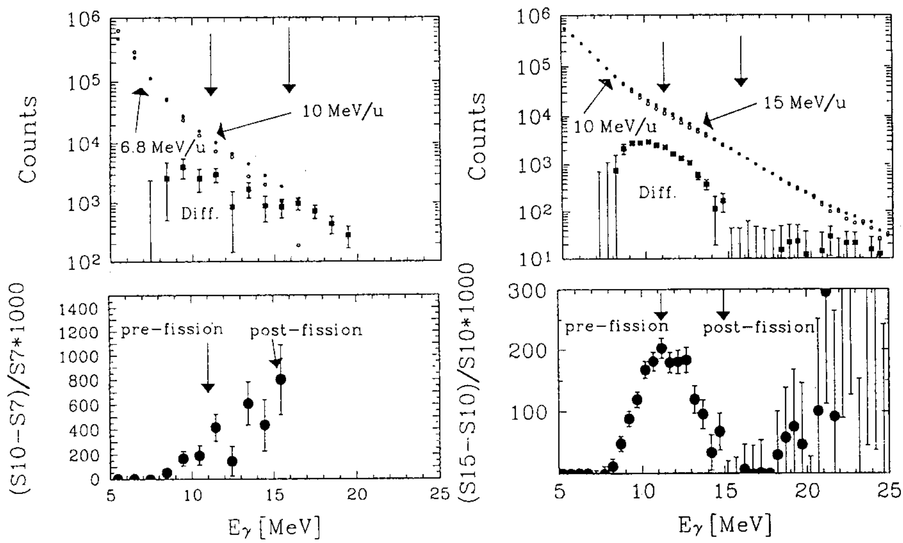

Fig. 10. Top panels: Measured high-energy γ-ray spectra from ^{272}Hs: at E_x = 105 and 230 MeV (left) and at E_x = 230 and 380 MeV (right) and the difference spectra. Bottom: the difference spectra divided by the spectrum at lower E_x presented in a linear scale. (From Ref. [21].)

The above experiment has allowed to study the GDR decay of the hot very heavy nucleus with $Z \approx 108$. In addition, it has also yielded an estimate of the lower limit for the lifetime of the hot heavy nucleus with $A \approx 272$. From the difference spectra one can conclude that fission does not start before the nucleus cools down to E_x = 230 MeV. The time needed for the compound nucleus to cool from E_x= 380 MeV to 230 MeV can be estimated by multiplying the average lifetime for the neutron evaporation in this E_x range by the average number of evaporated neutrons ($\approx$ 13). The lower limit for the lifetime of the hot heavy nuclei with $A \approx 272$ is then $\tau \approx 5 \cdot 10^{-21}$ s. However at E_x= 105 MeV some prefission component is still observed, yielding $\tau \approx 2.5 \cdot 10^{-20}$ s [21].

2.8. Isospin mixing at high excitation

The studies of hot nuclei with the GDR-decay as a probe which we have discussed up to now have been possible because the GDR couples to large amplitude fluctuations of the nuclear surface, and because the decay of the GDR is fast. Another important property of the GDR is that it is a pure isovector excitation. As a result, the $E1$ transitions between states of the same isospin in $N = Z$ nuclei are forbidden. In the absence of the isospin mixing, in $N = Z$ compound nuclei formed in heavy-ion fusion reactions with $N = Z$ targets and projectiles, only the states with the total isospin $T = 0$ can be populated. These states will then decay only to $T = 1$ final states, for which the density is much lower than for the states with $T = 0$. The γ-ray yield due to the statisically populated GDR in this reaction should therefore be small in case of the pure isospin. If the isospin is mixed, on the other hand, then the $T = 1$ initial states will also be populated. These states will decay to the more numerous $T = 0$ final states, resulting in an enhancement of the high energy γ-ray production cross-section. In $N \neq Z$ compound nuclei, the $E1$ decays are not isospin forbidden and thus the γ-ray yield depends much less on the isospin mixing.

Early work by Harakeh *et al.* [22] done at NPL Seattle demonstrated the technique in a measurement of the isospin mixing in ^{28}Si at $E_x = 34$ MeV. In the recent work done in Seattle [23] the isospin mixing in ^{28}Si at $E_x = 47$ and 63 MeV and in ^{26}Al at $E_x = 33$, 42 and 62 MeV has been deduced from a comparison of γ-ray production cross-section for heavy-ion fusion-evaporation reactions forming $N = Z$ and neighbouring $N \neq Z$ nuclei. The isospin violating spreading width which characterizes the admixture of $T = 1$ states into $T = 0$ states has been extracted by comparing the data and the statistical model calculations involving isospin. Fig. 11 shows the deduced isospin mixing coefficient. A non-trivial result is that the mixing becomes small at high E_x.

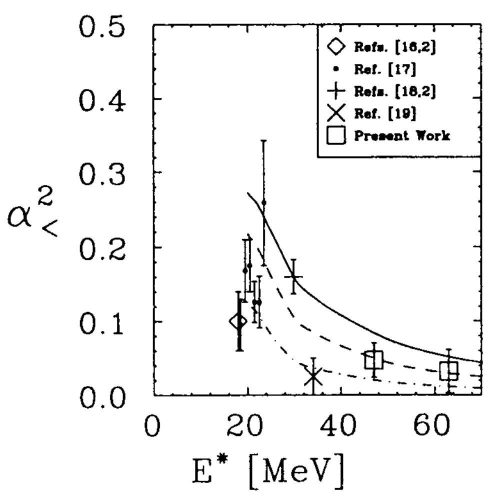

Fig. 11. Isospin mixing as a function of excitation energy in ^{28}Si. (From Ref. [23].)

3. GMR studies

Another GR of interest for studies of the properties of hot nuclei is the Giant Monopole Resonance, GMR. The GMR has attracted great interest because of its direct relation to the nuclear compressibility (*e.g.* [24, 25]). Thus studying GMR in hot nuclei may bring information about the temperature dependence of the compressibility in finite nuclei and, eventually, in the nuclear matter.

The GMR may be excited in heavy-ion fusion reactions in a similar way as are the other GR's. However, the single photon decay channel is not available for monopole transitions, which may proceed practically only by the electron-positron, $e^+ e^-$, pair emission. The internal conversion process is much less likely at the GMR energies. The branching ratio for the monopole pair transitions from the GMR induced in a typical heavy-ion reaction is of the order of 10^{-8}, to be compared to that for the GDR γ-decay being 10^{-3}. The main difficulty in studying the monopole transitions in hot nuclei is, however, connected not with their low yields but with the fact that all the higher multipolarity transitions may also proceed via the $e^+ e^-$ pair emission. The latter therefore does not provide a unique signature of the monopole transition. In fact, the dilepton spectrum from a hot nucleus is expected to be dominated by the pair decay of the GDR. The $E0$ pair decay is expected to be $\sim$ 3 to 4 orders of magnitude weaker than the $E1$ pair decay.

A systematic study of the dilepton mode of deexcitation of the GR vibrations in hot nuclei has been started at the KVI Groningen in collaboration with Świerk and Cracow a few years ago. A special multidetector system - the Positron-Electron Pair Spectroscopy Instrument (PEPSI) has been constructed for this purpose [26]. The system is designed for measuring the $e^+ e^-$ pair spectra in the total energy range of about 10–40 MeV. It consists of a set of 32 magnetic filters. Each filter provides an approximately toroidal field thus acting as a mini-orange spectrometer. PEPSI permits to distinguish the electrons from positrons. Each of the 12 filters selecting positrons is surrounded by 6 electron filters. The PEPSI response function can be divided into four bins depending on the pair opening angle. Since the pair opening angle allows for some differentiation of the multipolarities an experimental enhancement of the monopole contribution on the level of 3–5 can be obtained. The needed factor is however of the order of one thousand. Another possibility to obtain a relative enhancement of the $E0$ spectra is to choose the reaction in which the isovector dipole strength is suppressed. One way to attain this suppression is to make use of the isospin selection rule, as discussed in section 2.8.

A search for the isoscalar monopole strength has been done for the ^{28}Si compound nuclei, populated at E_x = 50 MeV by ^{3}He + ^{25}Mg (T = 0,1)

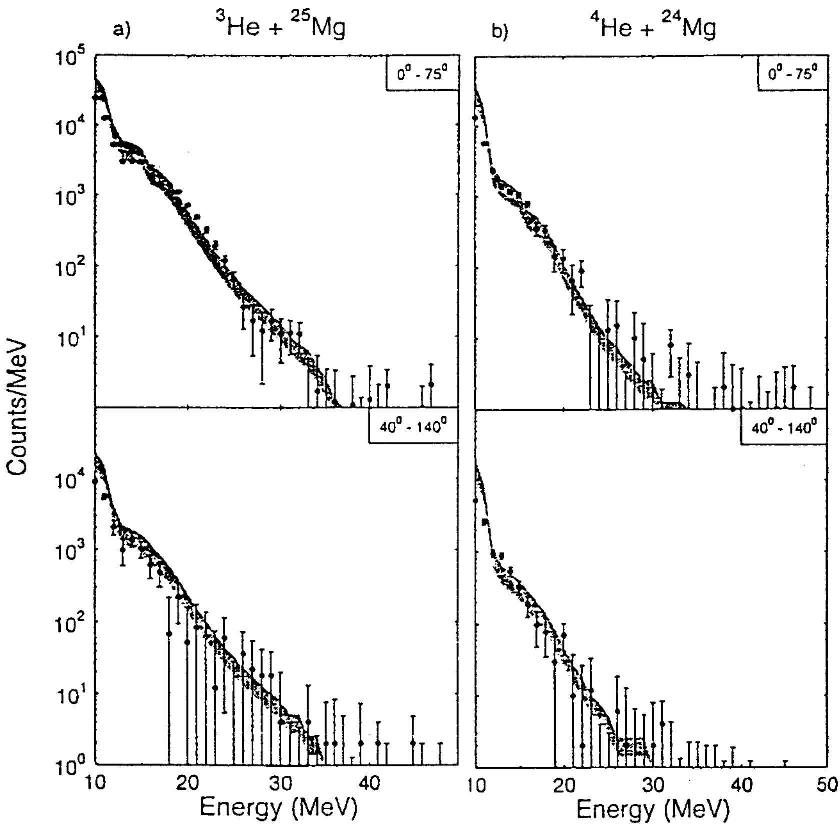

Fig. 12. The e$^+$ e$^-$ total energy spectra for the ^{3}He + ^{25}Mg and ^{4}He + ^{24}Mg reactions for two ranges of opening angles. Shaded areas: the measured photon yield converted to dilepton spectra. (From Ref. [27].)

and ^{4}He + ^{24}Mg ($T = 0$) reactions with 31 and 48 MeV projectile energies, respectively [27, 28]. The experiments were done at KVI Groningen. The pair spectra were measured with PEPSI and the corresponding γ-ray spectra with a large $NaI(Tl)$ spectrometer. In Fig. 12 the total energy spectra of e$^+$ e$^-$ pairs measured for these reactions for the two ranges of openning angles are compared with the spectra obtained by multiplying the experimental γ-ray spectra with the internal pair conversion coefficient for electric dipole transitions. These coefficients are the largest possible and thus the procedure permits to determine the upper limit of the pair yield due to transitions with multipolarity $L > 0$. Thus any excess of the measured pair yield over the converted one could be attributed to the monopole contribution. Fig. 12 shows good agreement between the measured dilepton yield and the calculated one, in agreement with the presumption that most of the measured dilepton strength comes from the internal pair conversion process of the photon decay channel. In the energy range of 17–23 MeV, where the expected GMR yield should have maximum, the extracted integrated excess cross-section is below 1 nb.

A similar experiment has subsequently been done with the PEPSI system installed at the superconducting LINAC accelerator at Stony Brook [29]. The $T_z = 0$ reaction $^{16}O + ^{12}C -> ^{28}Si$ has been used with $E_x = 50$ MeV. The dilepton cross-section, integrated over the transition energy region 15–30 MeV, was determined to be $\sigma(e^+e^-) = (84 \pm 6)$ nb. This agrees with the CASCADE calculations for E1 pair decay and permits to determine only an upper limit for the monopole strength. This shows how difficult experimentally are these studies. It seems already to be a success that the measured pair spectra in the energy range of GMR are in agreement with the predicted results. Further improved, highly selective techniques for observing the monopole pair transitions are needed in order to unambiguously determine the GMR properties in hot nuclei from the dilepton spectra.

4. Summary and future possibilities

We have shown that the improved experimental methods of the Giant Dipole Resonance studies in hot nuclei allowed to explain the behaviour of the GDR parameters in a broad range of nuclear masses, excitation energies and angular momenta, implying the stability of the GDR itself. The increase of the measured GDR width in hot nuclei has been understood as being due to the coupling of the collective dipole vibrations to the shape degrees of freedom in excited nuclei, demonstrating also the importance of fluctuations in such systems consisting of the finite number of nucleons.

The universality of the GDR and its additional features such as the coupling to the large amplitude fluctuations of the nuclear surface, the fast decay and the pure isovector character provide possibilities to study the properties of hot, fast rotating nuclei. We have presented some examples of such studies.

We have shown that the thermal fluctuation model of shape and orientation has been extensively studied in the region of high spins. Some tests at low spins as a function of temperature remain to be done. Such studies are presently being undertaken at the Warsaw Cyclotron equipped with the newly built multidetector system JANOSIK [30]. We should also look for an experimental evidence for non-adiabatic effects at high temperature.

Presently new possibilities of more exclusive experiments using large HPGe arrays are openning up [31]. They will allow to study the GDR corresponding to a particular decay channel, leading to a specific final nucleus, and thus permitting a more accurate definition of the temperature at the moment of the decay. Gamma-ray spectra measured in such experiment cannot be compared directly with statistical model CASCADE calculations. The need for a reliable Monte Carlo CASCADE code is therefore growing.

Interesting possibilities which are also openning up are connected with the reaction mechanism studies. Thus, *e.g.* , it was predicted long time ago by Świątecki [32] that under certain conditions fusion reactions involving mass symmetric entrance channels could take more time to produce an equilibrated compound nucleus than the mass asymmetric reactions leading to the same final nucleus. This behaviour is dependent on the entrance channel asymmetry and the effective fissility of the composite system determining the delay caused by dissipative effects. The GDR is a very convenient probe for studying these effects since the γ-ray decay of the GDR excited in a fusion reaction is now well understood and the distribution of the GDR strength is sensitive to the shape of the emitting system. Such dynamical effects have been already discussed in the context of the GDR decay [33, 31] but more experimental evidence is needed.

Taking adventage of the knowledge of the GDR-decay one can also study the bremsstrahlung γ-ray emission in heavy-ion reactions at low projectile energies, above about 6 MeV/u. It was suggested [34] that at projectile energies around 10 MeV/u, where the relative importance of the Fermi motion of nucleons in the colliding nuclei and of the Pauli blocking are expected to increase, the bremsstrahlung photon production should be sensitive to differences in the neutron-proton phase space distribution.

Finally, we should think about studying GDR in exotic nuclei which may be reached with radioactive beams.

As far as the GMR studies are concerned the location of the strength in some $N = Z$ nuclei followed by studies of the dependence of the GMR parameters on the temperature would be the nearest goals.

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