Excitation-Energy Dependence of the Giant Dipole Resonance Width

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High-energy γ rays have been measured in coincidence with heavy fragments in deeply inelastic reactions of ^{136}Xe+^{48}Ti at 18.5 MeV/nucleon. The giant dipole resonance (GDR) strength function is deduced from an analysis of the photon spectra within the statistical model. The GDR width Γ is studied as a function of the fragment excitation energy E^*. A saturation at about $\Gamma = 10$ MeV is observed for $E^*/A \geq 1.0$ MeV.

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The giant dipole resonance (GDR) in nuclei constitutes a universal collective excitation mode involving all nucleons, and is well established in all nuclei with a rather weak nucleus mass dependence for its energy position and width. It has also been verified that due to its simple collective nature the GDR couples to other modes of excitation, changing only slowly its characteristic properties. This in turn has been used to infer the properties of other such modes of excitation, for example, the rotation-induced deformation of nuclei, by observing the broadening of the width of the giant resonance built on rotational states as a function of angular momentum.

These studies have been performed generally in fusion reactions between two nuclei involving heavy-ion beams. At low incident energies this leads to compound nuclei with well-defined properties. However, with increasing energy incomplete fusion processes set in leading to a broad range of reaction products with different excitation energies. To study the properties of nuclei at well-defined excitation energies, the linear momentum transfer in the heavy-ion reaction has been measured simultaneously [1]. In the attempt to produce highly excited nuclei up to their limit of stability a possible alternative to fusion reactions are deep inelastic collisions between two heavy nuclei, where large fractions of the kinetic energy of relative motion are converted into internal excitation. From a full kinematic reconstruction of the observed binary process, the primary total excitation energy can be inferred. It has been realized early on that this could be a viable approach to studying the giant dipole resonance characteristics in highly excited nuclei [2]. However, the substantial experimental effort for an efficient detection of the decay photons in coincidence with the binary fragments which are spread over a large angular range has limited its application.

In the present Letter we report a successful measurement using this technique in an experimental setup with almost full angular coverage. The results, in our opinion, establish unambiguously for the first time the saturation of the spreading of the giant resonance width with excitation energy in very *hot* nuclei. Our findings are in qualitative agreement with certain model predictions [3] but are in strong disagreement with other recent experimental results [4].

The system ^{136}Xe+^{48}Ti was studied at an incident energy of 18.5 MeV/nucleon. In this energy regime deeply elastic reactions dominate the total reaction cross section [5]. A 175-μg/cm^2 ^{48}Ti target was bombarded by a ^{136}Xe beam (3×10^9 ions/s) provided by the UNILAC accelerator at GSI Darmstadt. Velocity vectors of heavy fragments were reconstructed by means of twelve large-area position-sensitive parallel-plate avalanche counters (PPAC's) [6] covering about 75% of the solid angle in the forward hemisphere. The PPAC's were located symmetrically around the beam axis in three planes and provided information on the time of flight and the position of heavy fragments ($Z > 10$). In a full kinematic reconstruction using mass and momentum conservation primary quantities like fragment masses (M_1,M_2) and total kinetic energy losses (TKEL) were determined [7].

High-energy photons were measured in three arrays comprising 7, 40, and 19 BaF_2 scintillation counters located at laboratory angles of 50°, 90°, and 150° and at distances to the target of 116, 40, and 59 cm, respectively. The energy calibration was performed with cosmic-ray muons as a high-energy reference point and with standard radioactive sources (^{88}Y,^{60}Co) in the low-energy range. The intrinsic Ra α activity of the BaF_2 detectors was used to control and stabilize the energy calibration during the whole run. The cosmic-ray background was eliminated by subtracting the appropriate beam-off energy spectra. Light charged particles and neutrons were discriminated by means of time of flight with respect to the pulsed beam. An overall time resolution of 0.8 ns was achieved. Additionally, pulse-shape analysis [8] of the intrinsic detector response was used to discriminate charged particles applying different integration times of 40 ns and 2 μs, respectively, for the BaF_2 energy signals. Only events with γ-ray energy above a threshold of ≈ 2 MeV in coincidence with two heavy fragments were recorded.

To investigate the excitation energy dependence of the GDR width, exclusive γ-ray spectra were generated associated with binary fragments and different energy bins in the total kinetic energy loss (TKEL=150–250, 250–350, >350 MeV). To facilitate the comparison well-defined exit channels have been selected in the analysis by applying an asymmetric mass cut for the heavy fragments ($M_1 < 60$, $M_2 > 122$). The exclusive γ-ray multiplicity spectra were transformed into the center of mass of the combined system and integrated in 4π assuming isotropic emission in the center of mass. Three features in the energy spectra can be identified as shown by the data accumulated without TKEL conditions (Fig. 1): statistically emitted photons ($E_\gamma < 10$ MeV) after particle evaporation, hard photons above 25 MeV from proton-neutron bremsstrahlung [9,10], and an excess yield in the energy region between 10 and 25 MeV ascribed to the γ decay of the GDR. To separate statistical photons from bremsstrahlung, the experimental data above 30 MeV have been fitted with an exponential function (dotted line) with an inverse slope parameter of 6 ± 1 MeV. This value is in accordance with current systematics on hard photon emission [10]. The bremsstrahlung yield has been

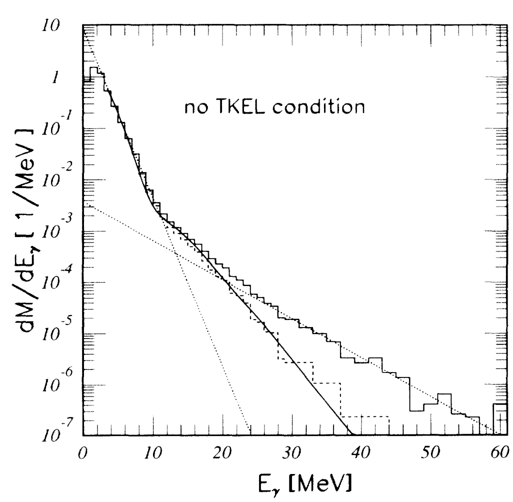

FIG. 1. Energy differential photon multiplicity. The soft photon part and the bremsstrahlung contribution have been parametrized by exponentials and fitted below 10 MeV and above 30 MeV, respectively (dotted lines). The statistical photon multiplicity deduced by subtracting the bremsstrahlung (dashed histogram) is also shown in comparison to the CASCADE calculation (solid curve).

removed by subtracting this exponential contribution as illustrated in Fig. 1 for the γ-ray spectrum with no TKEL condition.

Statistical model calculations with the evaporation code CASCADE [11,12] have been performed to analyze the resulting thermal photon spectra. Two separate calculations were performed for target and projectile mass, respectively, and for the same nuclear temperature, i.e., assuming a splitting of the total kinetic energy loss proportional to the fragment mass ratios. The sum of the resulting photon spectra was compared to the experimental data. It turns out, however, that at photon energies above 10 MeV the spectrum is dominated by the contribution from the heavier Xe-like fragments.

The angular momenta of the fragments entering the statistical model calculations were assumed to be given by model predictions for the deeply inelastic reactions: i.e., the "rolling limit" (^{136}Xe, 19.7$\hbar$; ^{48}Ti, 13.9$\hbar$) for the quasielastic component (small TKEL) and by the "sticking limit" (^{136}Xe, 48.1$\hbar$; ^{48}Ti, 8.5$\hbar$) [5,13] for the deep inelastic component. Angular momentum effects have, however, only little influence on the result of the calculations. A constant level density parameter $a = A/8$ has been adopted throughout.

The calculations have been performed with a strength function of Lorentzian shape with centroids at $E_{GDR} = 15.3$ and 18.5 MeV for Xe- and Ti-like fragments, respectively, and 100% energy-weighted sum-rule (EWSR) strength. Furthermore, an electric isoscalar giant quadrupole resonance (ISGQR) with a width of 7 MeV and resonance energies of 12.6 and 17.9 MeV for Xe and Ti, respectively, as well as an electric isovector giant quadrupole resonance (IVGQR) with resonance energies of 24.7 and 34.9 MeV and widths of 7 MeV have been taken into account in the CASCADE calculations in agreement with systematics [14].

For comparison with the experimental data the CASCADE spectra were folded with the detector response function of the BaF_2 detectors which was extracted from Monte Carlo shower simulations using the code GEANT3 [15]. The photon spectrum without a condition on TKEL (Fig. 1), obtained after subtraction of the bremsstrahlung contribution, is reproduced up to energies above 30 MeV with a statistical model calculation for an average total excitation energy of 310 MeV.

In the analysis of the exclusive photon spectra shown in Fig. 2 the total excitation energy can be only approximately identified with the total kinetic energy loss. Preequilibrium energy losses from light particle emission lower the excitation energy compared to the measured TKEL. According to systematics [16] these losses increase with TKEL and reach 10% for the highest TKEL bin. CASCADE calculations with correspondingly modified excitation energies reproduce the exclusive photon spectra as shown in Fig. 2.

The shape of the GDR has been extracted from the exclusive photon spectra following a procedure given by

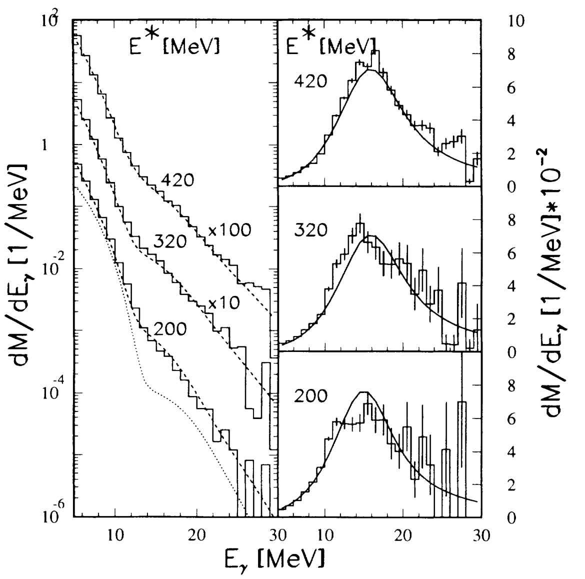

FIG. 2. Measured statistical photon multiplicity for three TKEL bins and corresponding CASCADE calculations for the quoted total excitation energies E^*. The dotted line indicates the calculated contribution from Ti-like fragments for the case $E^*=200$ MeV (left). The strength functions deduced by dividing the measured data by the ratio $\sigma_{CAS}(E_\gamma)/\sigma_{abs}(E_\gamma)$ are shown on the right-hand side. For comparison the GDR strength functions used in the CASCADE calculations are also indicated.

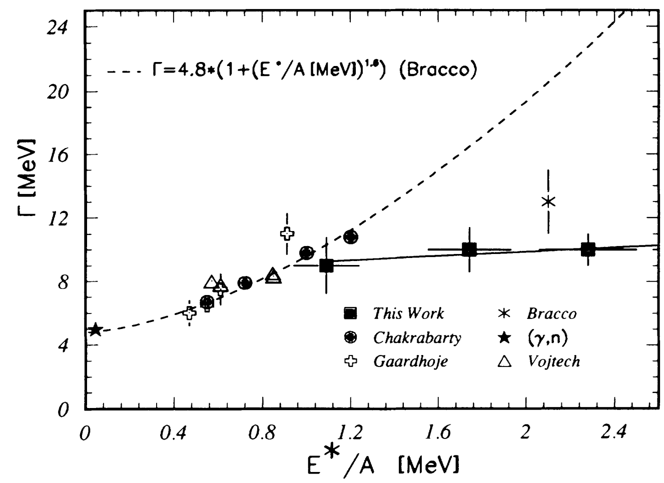

FIG. 3. GDR width as a function of the excitation energy per nucleon. The dashed line represents a fit to the Sn data [1,18–21]. The error bars for the GDR width in the present work include statistical errors as well as systematic uncertainties arising from different choices of input parameters for the CASCADE calculation while the horizontal bars represent the uncertainty in the excitation energy. The solid line corresponds to a linear fit to the present results.

Gundlach *et al.* [17]. The statistical model phase space is eliminated by dividing the measured energy spectra by the ratio $\sigma_{CAS}(E_\gamma)/\sigma_{abs}(E_\gamma)$, where $\sigma_{abs}(E_\gamma)$ represents the Lorentz-shaped photon absorption cross section and $\sigma_{CAS}(E_\gamma)$ is the energy differential photon cross section obtained with the statistical model code CASCADE, respectively. The same GDR width is used as an input parameter for the CASCADE calculation and the width of the Lorentz function $\sigma_{abs}(E_\gamma)$. The width parameter is varied in the full CASCADE calculation until optimum reproduction of the measured photon spectra is achieved.

The exclusive photon spectra for three excitation energies (left) and the corresponding extracted GDR strength functions are displayed in Fig. 2. The comparison illustrates that the data can indeed be reproduced with 100% of the energy-weighted sum-rule strength and resonance energies given by ground-state systematics. The GDR widths, on the other hand, are approximately constant around 10 MeV and thereby substantially broader than the ground-state widths of 4–5 MeV. It should be noted that the observation of an almost constant resonance width is insensitive to the particular choice of CASCADE parameters such as, e.g., the level density parameter *a*.

Figure 3 shows the systematics of the GDR width as a function of the excitation energy per nucleon in comparison to previous data obtained in the Sn region [16–19]. A strong increase of the width described by the function $\Gamma_{GDR}=4.8[1+(E^*/A)^{1.6}]$ was found [1] up to $E^*/A=1.0$ MeV. A saturation of the GDR width at higher excitation energies as suggested by Bracco *et al.* [1] is clearly established with the present data. While the increase of the width at lower excitation energies is generally interpreted as arising from deformation effects induced by the angular momentum there are first theoretical attempts to explain the almost constant GDR width at higher temperatures. Microscopic calculations by Bortignon *et al.* studying the coupling of particles and vibrations [22] indicated only a weak variation of the GDR spreading width with temperature. This result is substantiated in more recent microscopic calculations involving long- and short-range correlations for spherical nuclei [23] which show a remarkable insensitivity of the GDR width on temperature, in line with our present findings. In case this theoretical result is corroborated for heavy and deformed nuclei too, we might interpret the constant width of the GDR at higher excitation energy as a consequence of the fact that for $E^*/A \geq 1.0$ MeV the damping appears to be governed by mean-field effects which are inherently unaffected by temperature. This suggestion, however, requires further experimental and theoretical investigations.

In conclusion, the giant resonance γ decay has been investigated in hot nuclei of rather well-known excitation energies produced in deeply inelastic collisions of heavy ions. Analyzed within the framework of the statistical model, the width of the giant resonance has been deduced and studied as a function of the excitation energy. A saturation of the width around $\Gamma=10$ MeV is observed for $E^*/A > 1.0$ MeV which calls for further theoretical studies.

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