Electromagnetic Excitation of the Double Giant Dipole Resonance in ^{136}Xe

R. Schmidt,(3) Th. Blaich,(5) Th. W. Elze,(4) H. Emling,(3) H. Freiesleben,(1) K. Grimm,(4) W. Henning,(3),(6) R. Holzmann,(3) J. G. Keller,(1) H. Klingler,(4) R. Kulessa,(2),(3) J. V. Kratz,(5) D. Lambrecht,(5) J. S. Lange,(1) Y. Leifels,(1) E. Lubkiewicz,(2) E. F. Moore,(3) E. Wajda,(2),(3) W. Prokopowicz,(2) Ch. Schütter,(4) H. Spies,(4) K. Stelzer,(4) J. Stroth,(3) W. Walus,(2) H. J. Wollersheim,(3) M. Zinser,(3),(6) and E. Zude(3),(6)

(LAND Collaboration)

(1)*Institut für Experimentalphysik, Ruhr Universität Bochum, D-4630 Bochum, Germany*
(2)*Institute of Physics, Jagiellonian University, PL-30-059 Cracow, Poland*
(3)*Gesellschaft für Schwerionenforschung, D-6100 Darmstadt, Germany*
(4)*Institut für Kernphysik, Johann Wolfgang Goethe-Universität, D-6000 Frankfurt, Germany*
(5)*Institut für Kernchemie, Johannes Gutenberg-Universität, D-6500 Mainz, Germany*
(6)*Institut für Physik, Johannes Gutenberg-Universität, D-6500 Mainz, Germany*

(Received 30 September 1992)

The nuclear response of a medium-mass nucleus (^{136}Xe) to electromagnetic excitation in a near-relativistic heavy-ion collision was investigated in the reaction ^{136}Xe(0.7A GeV)+Pb. From an exclusive measurement of the neutron decay of the excited ^{136}Xe projectiles, strong excitations of giant resonances and, in particular, of the double isovector giant dipole resonance were identified. A resonance energy of 28.3 ± 0.7 MeV, a width of 6.3 ± 1.6 MeV, and a total cross section of 215 ± 50 mb were found for the double giant dipole resonance.

PACS numbers: 24.30.Cz, 25.75.+r

Very large probabilities are expected for the electromagnetic excitation of high-lying collective nuclear modes, such as giant resonances, in peripheral heavy ion collisions at energies in the (near) relativistic regime. With such high probabilities for single-step excitations, also multistep excitations become probable. The excitation of multiphonon states, in particular of the double giant dipole resonance, are predicted to become observable with cross sections up to several hundred millibarns [1]. In a number of radiochemical measurements [2] it was shown that electromagnetic excitation followed by neutron emission contributes significantly to the process of fragmentation in peripheral heavy ion collisions. More recently, direct observations of the giant dipole resonance excitation in light nuclei were obtained with particle counter techniques [3,4]. Here, we report on a first exclusive measurement of the electromagnetic excitation and the decay of giant resonances in a medium-heavy nucleus. ^{136}Xe projectiles were excited in collisions with Pb target nuclei at a laboratory energy of 0.7A GeV and from the exclusive measurement of the subsequent neutron decay the excitation energy was unambiguously reconstructed. We observe, in particular, the double isovector giant dipole resonance being excited with considerable cross section.

The experiment was performed at the heavy ion synchrotron (SIS) facility at GSI, Darmstadt. We used ^{136}Xe projectiles of 0.7A GeV with a typical beam intensity of 10^4 particles per second, and lead and carbon targets with 1.38 and 0.26 g/cm^2 thickness, respectively. The experimental setup is shown in Fig. 1. It meets the conjecture that the ^{136}Xe projectile, excited in a peripheral collision, deexcites by emission of neutrons and subsequent gamma decay of the heavy residue. It is known that giant resonances in heavy nuclei almost exclusively decay via neutron emission. The primary projectile excitation energy is obtained by reconstructing the final state invariant mass from the four-momenta of the particles and of the emitted gamma rays in the laboratory frame.

As shown in Fig. 1, the trajectories of the projectiles and of the projectile fragments were traced by means of four plastic scintillation counters, the thickness of which varied between 0.1 and 1 mm. These detectors delivered position information in both dimensions perpendicular to the beam axis and also provided an excellent time-of-flight (TOF) resolution. Beam fragments as well as noninteracting projectiles entered the dipole magnet ALADIN [5] which had a large rectangular gap, 1.6 m

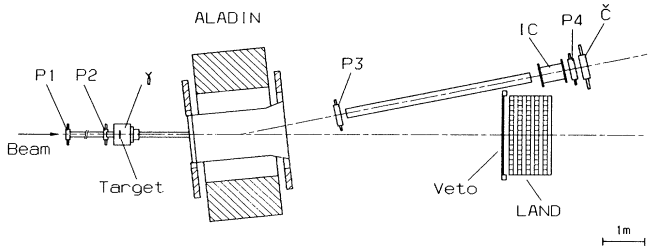

FIG. 1. Schematic view of the experimental setup. Shown are the beam and fragment tracking counters (P1–P4), the ionization chamber (IC), the Cherenkov detector (C), the dipole magnet (ALADIN), the gamma detector array (γ), the neutron detector (LAND, Veto), and parts of the beam line.

wide and 0.48 m high. The magnetic field was adjusted to deflect projectiles by 11.3°. The nuclear charge of the fragments was measured by a combination of a multisampling ionization chamber and a glass (Schott SF3) Cherenkov counter, yielding a resolution $\sigma_z = 0.22$. The positional tracking of the heavy ion together with measurements of the nuclear charge and time of flight delivered the information on its nuclear mass ($\sigma_A = 0.9$), and on the fragment momentum ($\sigma_p/p = 2.5\times10^{-3}$; p denotes the absolute value of the momentum). The angular resolution for the fragment was limited by lateral straggling in the target resulting in $\sigma_\Theta \approx 2$ mrad. The limited mass resolution did not prevent unambiguous fragment identification, since the decay neutrons are detected and counted as discussed in the following.

For the neutron measurement, we developed a large area (2×2 m^2) neutron detector (LAND) with high detection efficiency and multiple-hit capability. The detector is built from interspersed iron converter and plastic scintillator sheets with a total thickness of 1 m. The essential feature of accurate position and TOF information is achieved by modularizing the detector into 200 elements. The front face of the LAND is covered by a plastic "veto" wall (40 elements) which allows the identification of charged particles. A complete report on the detector layout and specifications, its performance, and the calibration procedure was published earlier [6]. The LAND was positioned 10 m behind the target and thus covered an angular acceptance of $\gtrsim 200$ mrad, which is larger than the measured opening cone of about 40 mrad for the forward emitted neutrons. The neutron momentum resolution amounts to $\sigma_p/p \approx 1.5\times10^{-2}$ and the neutron angular resolution to $\sigma_\Theta \approx 10$ mrad. The related resolution for the reconstructed excitation energy E^* depends on neutron energy and the number of emitted neutrons; for the one- (three-) neutron channel we estimate a contribution $\sigma_{E^*} = 0.8$ (1.7) MeV to the total resolution in E^*. As we discuss in Ref. [6], non-Gaussian tails with an intensity of 2% appear in the detector response for the neutron TOF and momentum, which are due to events where the first neutron interaction in the LAND does not produce visible light and only secondary interactions are observed.

An array of 48 BaF$_2$ scintillation counters was arranged around the target to measure the γ radiation emitted after neutron evaporation. These detectors covered the forward hemisphere such that 80% of the Lorentz-boosted solid angle for gamma rays from the projectile fragment was subtended. Tests with radioactive sources and extensive Monte Carlo simulations revealed that, on the average, 26% of the total γ-ray energy is converted into visible energy, an effect which was taken into account in the analysis. The gamma measurement was severely affected by radiation from atomic processes, i.e., production of δ electrons and subsequent x-ray emission and bremsstrahlung. This effect, however, could experimentally be determined by triggering on ^{136}Xe projectiles which did not undergo a reaction. These atomic effects lead to a nearly Gaussian distributed energy deposit (mean energy 5.5 MeV, $\sigma = 1.7$ MeV) in the BaF$_2$ array for the lead target; this was later subtracted out. In total, the γ measurement contributed to the resolution of the reconstructed excitation energy E^* with $\sigma_{E^*} = 2.2$ MeV for the Pb target, and dominated the overall resolution. For the C target, the atomic effects were found to be negligible. Finally, a measurement without a target was performed, which served to determine the background from reactions in the detector material or covering foils.

The data analysis proceeded in several steps: First, Xe fragments were identified on the basis of the nuclear charge measurement. Then the number of coincident neutrons in the LAND was determined. The number of neutrons was checked for consistency by comparing to the measured fragment mass; this procedure was impaired to some extent by the modest fragment mass resolution (see above). Second, for each reaction channel involving a certain number of neutrons we determined the invariant mass and thus the primary excitation energy from the measured momenta of the fragment and the neutrons, and the energies and angles of the gamma rays. Because of the finite efficiency (~85%) and the finite multiple-hit resolution of the LAND, small channel-dependent corrections were necessary, which were obtained from Monte Carlo simulations based on the measured LAND performance (details can be found in [7]). Finally, the spectra for the reaction channels with up to three decay neutrons were added together; channels with more neutrons did not contribute significantly. In Fig. 2 we show the resulting

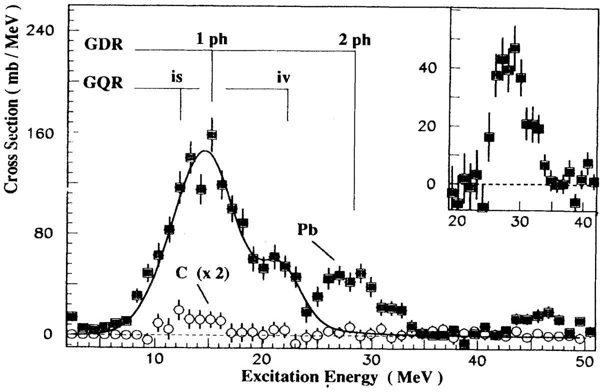

FIG. 2. Experimental results for ^{136}Xe projectile excitation on a Pb target (squares) and a C target (circles); only statistical errors are given. The spectrum for the C target is multiplied by a factor 2 for better presentation. The resonance energies for the one- and two-phonon giant dipole resonance and for the isoscalar and isovector quadrupole resonances are indicated. The solid curve reflects the result of a first-order WW calculation (see text) for the Pb target. The inset is obtained after subtracting the WW calculation from the measured Pb spectrum and displays the energy range relevant for the DGDR.

excitation energy spectrum for ^{136}Xe, obtained with the Pb and C targets. These spectra are corrected for background using the measurement without target.

The total energy integrated cross sections obtained from lead and carbon targets (Fig. 2) are 1.85 ± 0.1 and 0.07 ± 0.01 b, respectively; the quoted errors include estimates of systematic effects. An estimate of the electromagnetic cross section for the carbon target (see below) results in 0.03 b. By adopting a scaling of the nuclear cross section with the target radius (see Ref. [8]), we thus deduce from the C data that the nuclear cross section contributes only ~ 100 mb for the Pb target, and thus the overwhelming fraction of the measured cross section is due to electromagnetic excitations. We therefore compare our experimental excitation energy spectrum for the Pb target to calculations of the electromagnetic excitation within the framework of the Weizsäcker-Williams method (WW) of virtual quanta [9]. The basic ingredients of such a calculation are the dipole and quadrupole nuclear photoabsorption cross sections, which have to be folded with the spectrum of virtual photons. Higher multipolarities can be neglected because of their expected low cross section. For the giant dipole resonance (GDR) we extract the photoabsorption cross section from the systematics summarized in Ref. [10], giving a resonance energy of 15.2 MeV and a width of 4.8 MeV (if approximated by Lorentz distribution). For the giant quadrupole resonances (GQR) we use the systematics presented in Ref. [11] and interpolate the values for ^{136}Xe. For the isoscalar GQR we deduce a resonance energy of 12.3 MeV, a width of 4.0 MeV, and a strength corresponding to 70% of the energy-weighted sum rule (EWSR). The uncertainties to which these values can be obtained are on a 10% level. For the isovector part of the GQR, however, only a small body of data is available. The scarce data for heavy nuclei ($A > 100$) scatter between 22 and 26.5 MeV for the resonance energy, 3.5 and 7 MeV for the width, and 27% and 133% depletion of the EWSR. Another important ingredient in such a calculation is the minimum internuclear distance below which nuclear absorption obscures the process of electromagnetic excitation. Here we used the parametrization for the minimum distance proposed in [8] and [12]. Furthermore, we take into account that the effective beam energy is slightly reduced (2.7%) due to energy loss in the target. The calculated spectrum was folded with the instrumental resolution.

In Fig. 2 we compare the excitation energy spectrum obtained for the Pb target with the result of our WW calculation, which takes into account single-step excitations only. For this calculation we start from the parameters for the GDR and isoscalar GQR quoted above; the parameters of the isovector GQR—with the poor systematics in mind—however, we adjusted in a least squares fit to the measured spectrum in the excitation energy range up to 25 MeV. For the latter we obtain a resonance energy of 22.1 ± 0.7 MeV, a width $\lesssim 5.4$ MeV, and $(93 \pm 45)\%$ of the EWSR strength; it appears that these values are still compatible with the data systematics of Ref. [11]. There was no need to modify the parameters for the isoscalar GQR and the isovector GDR, except for the GDR strength, which was found to be reduced by $(35 \pm 4)\%$; this effect will be discussed below. Comparing our calculation with the experimental spectrum for the Pb target, we observe a remarkably good agreement for excitation energies ≤ 25 MeV (Fig. 2).

Above 25 MeV a prominent structure is observed for the Pb target, which is centered slightly below twice the excitation energy of the GDR. We assign this structure to the double isovector giant dipole resonance (DGDR) on the basis of the following arguments:

(i) The calculated virtual photon spectrum drops drastically for energies above 20 MeV. There is no known or expected collective resonance in ^{136}Xe which could account for the observed strength in a single-step excitation, and consequently, a multistep excitation is inferred. Only a second-step excitation built on the GDR can account for the observed strength; multiple GQR excitations are calculated to be negligible.

(ii) The result from the carbon target reveals a negligible strength at this excitation energy; therefore effects due to nuclear interaction can be excluded.

(iii) For the observed structure we extract a mean excitation energy of 28.3 ± 0.7 MeV and a width (FWHM) of 6.3 ± 1.6 MeV (see Table I, where values relative to that of the GDR are also quoted) after subtracting the calculated spectrum of single-step excitations (see inset of Fig. 2). In a harmonic approximation one would expect a DGDR resonance energy of 30.4 MeV with a width of 9.6 MeV [1]. From a (π^+,π^-) double charge exchange measurement on the ^{138}Ba isotone [13], the authors claim evidence for the DGDR with a resonance energy at twice the GDR energy and a width of 8.5 ± 2.6 MeV, which compares rather well with our result. Moreover, preliminary results from a measurement of the γ-decay branch of the DGDR in ^{208}Pb [14] reveals values for the resonance energy and width, relative to those of the GDR, which compare very well with the ratios observed here (Table I).

(iv) We measure a DGDR cross section of 215 mb with an error of 32 mb, which includes the statistical and systematic error. Uncertainties in the parametrization of the isovector GQR, however, contribute considerably to the error. Varying the parametrization for the isovector

TABLE I. Parameter values obtained for the double giant dipole resonance (DGDR) in ^{136}Xe. The second line gives the ratio of these values to the ones for the giant dipole resonance (GDR).

	Mean energy	Width (FWHM)	Cross section
DGDR	28.3 ± 0.7 MeV	6.3 ± 1.6 MeV	215 ± 50 mb
DGDR/GDR	1.86 ± 0.05	1.3 ± 0.4	0.21 ± 0.05

GQR within reasonable limits implied by the data systematics [10], we estimate this contribution to about 40 mb. We thus adopt an overall error of 50 mb for the DGDR cross section.

The electromagnetic DGDR cross section can be calculated in the harmonic oscillator approximation [1]. Using this model we calculate a DGDR cross section of 70 mb and, because of flux conservation, simultaneously obtain a reduction of the GDR cross section by 21%. A more elaborate model for multistep excitations delivered a DGDR cross section of 87 mb [15]. Both models significantly underestimate the measured DGDR cross section. Most likely, the harmonic approximation underlying the models of [1] and [15] is inappropriate, and the structure of the DGDR is more complex. In fact, the somewhat down-shifted resonance energy of the DGDR and its relatively narrow width are already indications of anharmonicity effects. The enhancement of the DGDR cross section relative to the calculation necessarily requires a further reduction of the GDR cross section because of flux conservation, and is thus qualitatively in accord with our observation of a 35% reduction. Since the presently available models [1,15] are based on the harmonic approximation, a quantitative estimate cannot be made. We finally remark that the γ measurement [14] for ^{208}Pb as well as a recent radiochemical measurement [8] also find indications of a DGDR cross section enhanced by a factor of about 2.

The single-step excitation of giant resonances in the projectile on two different target nuclei, an effect which would lead to an experimental signature similar to that of the DGDR excitation, was calculated to contribute only 14 mb to the cross section, and this contribution was subtracted in the cross section quoted in Table I. We also checked effects of mutual giant resonance excitation in projectile and target, but under the given experimental conditions, such an effect cannot contribute significantly to the cross section measured in this region of excitation energies relevant for the DGDR. Because of the experimental setup, decay products from target excitation are not detected, except the gamma rays, for which we have a solid angle of only 50%. It can be estimated that the simultaneous excitation of giant resonances in the target would shift the measured excitation energy upward by only 2–3 MeV, an effect within the present resolution.

Finally, we remark that an additional structure of low intensity appears at $45 \lesssim E^* \lesssim 50$ MeV. It coincides approximately in energy with the expected excitation energy of the three-phonon GDR ($\sim$45 MeV). This structure comprises less than 3% of the total cross section. At this low level, at present we cannot exclude instrumental effects. In particular, the effect of non-Gaussian tails on a 2% level in the TOF response of the LAND, as discussed above, might contribute to this structure. To this respect, more refined Monte Carlo studies of the detector response will be carried out.

In summary, through an exclusive measurement, we have established the dominant role of electromagnetic giant resonance excitations, leading to few neutron removal channels in peripheral heavy ion collisions at high bombarding energies. The data are consistent with the expected excitation of giant dipole and quadrupole resonances. In particular, we have observed the double isovector giant dipole resonance in ^{136}Xe. The large cross section and the fact that the width of the DGDR is still rather narrow gives hope that even higher phonon states can be studied in the near future.

We are grateful to the ALADIN collaboration for use of their magnet, we thank the SIS and UNILAC operating staffs for their efforts to provide reliable beams, and H. Folger for the target preparation. This work was funded by the German Federal Minister for Research and Technology (BMFT) under Contracts No. 06 BO 103 and No. 06 MZ 106, and by GSI via Hochschulzusammenarbeitsvereinbarungen under Contracts No. BO FRE, No. F ELE, and No. Mz KRD and partly supported by the Polish Committee of Scientific Research under Contract NO. PB1158/P3/92/02.

[1] C. A. Bertulani and G. Baur, Nucl. Phys. **A482**, 313c (1988); Phys. Rep. **163**, 299 (1988).
[2] J. C. Hill, F. K. Wohn, D. D. Schwellenbach, and A. R. Smith, Phys. Lett. B **273**, 371 (1991).
[3] D. L. Olson, M. Baumgartner, D. E. Greiner, P. J. Lindstrom, T. J. M. Symons, R. Wada, M. L. Webb, B. L. Berman, H. J. Crawford, and J. M. Engelage, Phys. Rev. C **44**, 1862 (1991).
[4] E814 Collaboration, Phys. Rev. C **45**, 2427 (1992).
[5] ALADIN Collaboration, GSI Scientific report, 1989 (unpublished), p. 292.
[6] LAND Collaboration, Nucl. Instrum. Methods Phys. Res., Sect. A **314**, 136 (1992).
[7] R. D. Schmidt, thesis, Universität Mainz, 1991 [GSI Report No. 91-35 (unpublished)].
[8] T. Aumann *et al.*, GSI Report No. 92-47 [Phys. Rev. C (to be published)].
[9] J. D. Jackson, *Classical Electrodynamics* (Wiley, New York, 1975), p. 520.
[10] B. L. Berman, At. Data Nucl. Data Tables **15**, 319 (1975).
[11] F. E. Bertrand, Annu. Rev. Nucl. Sci. **26**, 457 (1976).
[12] S. Kox, A. Gamp, C. Perrin, J. Arvieux, R. Bertholet, J. F. Bruandet, M. Buenerd, R. Cherkaoui, A. J. Cole, Y. El-Masri, N. Longequeue, J. Menet, F. Merchez, and J. B. Viano, Phys. Rev. C **35**, 1678 (1987).
[13] J. Bar-Touv and S. Mordechai, Phys. Rev. C **45**, 197 (1992).
[14] TAPS and 4π Collaboration, GSI Scientific Report, 1991 (unpublished), p. 41.
[15] W. J. Llope and P. Braum-Munzinger, Phys. Rev. C **45**, 799 (1992); **41**, 2649 (1990).