First Observation of the Coulomb-Excited Double Giant Dipole Resonance in ^{208}Pb via Double-γ Decay

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The photon decay of the relativistic Coulomb excitation of the single and double giant dipole resonance (GDR) in the target has been observed in the system $1A$ GeV ^{209}Bi on ^{208}Pb. For peripheral events which are dominated by relativistic Coulomb excitation, a large Lorentzian structure in the photon energy spectrum is peaked at 13.3±0.1 MeV with a width of 4.1±0.1 MeV, corresponding to the single GDR in the ^{208}Pb target. The sum energy of coincident γ-γ pairs shows a broad feature at 25.6±0.9 MeV with a Lorentzian width of 5.8±1.1 MeV, which we assign to the double GDR observed via the two-γ decay channel.

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The giant dipole resonance (GDR) is one of the most fundamental nuclear excitations. In a macroscopic picture, it corresponds to a collective oscillation of the proton liquid against the neutron liquid. According to the Brink-Axel hypothesis [1], giant resonances are also built on excited states. In particular, a state consisting of a GDR built on the ground state GDR should exist. In a harmonic oscillator model, this state is the two-phonon $E1$ excitation (GDR2). These multiphonon excitations test the harmonicity and collectivity of the (liquid drop) symmetry potential and the damping of these oscillations into states of more complicated structure. Several theoretical investigations have dealt with the properties of such states [2–5]. Two-phonon GDR excitations have been previously observed in pion double-charge-exchange reactions which produce the $\Delta\ T_z = \pm 2$ analogs of this collective state in the target nucleus [6, 7]. In contrast, Coulomb excitation followed by two-photon decay allows the direct identification of the GDR2 collective state in the T_z basis nucleus.

With the advent of relativistic heavy ion beams it is now possible to exploit the strong electromagnetic field of a relativistic projectile with large Z, to Coulomb excite the GDR with high probability. Because of the short time duration of the interaction, multiple excitation of the GDR becomes a very likely process, with cross sections of several hundred mb for the GDR2 in heavy systems at $\approx 1A$ GeV predicted by the Weizsäcker-Williams virtual photon method [8, 9]. Three recent experiments infer the existence of multiple Coulomb excitation of the GDR from particle decay channels [10–12].

In the present paper, we report the first experimental detection of the direct two-γ decay of the GDR2 in ^{208}Pb. This experiment was performed at the Heavy Ion Synchrotron (SIS at GSI Darmstadt), using the detector system TAPS (two-arm photon spectrometer) [13] and the forward wall (FW) of the 4π detector system [14]. The $1A$ GeV ^{209}Bi beam with an intensity of up to 3×10^6 particles per 4 s spill (10 s repetition rate) was incident on a 420 mg/cm^2 thick (98.7% isotopically enriched) ^{208}Pb target turned at 45° relative to the beam. TAPS is a modular system of 256 BaF_2 detectors with individual plastic veto counters arranged in four blocks. The geometrical setups used in the present experiment are described in Table I. The FW is a highly segmented large-area plastic detector which records charged particles emitted from the reaction zone at angles between 1° and 30° relative to the beam axis. The FW fires with very high efficiency for events where nuclear interactions have taken place. By requiring that the FW detect no charged particles, peripheral events can be selected where electromagnetic interactions dominate the reaction. This requirement is crucial for the observation of Coulomb-excited states because of the enormous background due to nuclear interactions in central events.

A very heavy system (i.e., ^{209}Bi + ^{208}Pb) provides a large two-step excitation cross section of the GDR2 ($\sigma \approx Z^4_{\mathrm{proj}}$). The choice of a moderately relativistic energy ($1A$ GeV) limits the direct one-step excitation of states in the region of the GDR2 [15], due to the absence of high frequency components in the virtual photon spectrum. Since both the projectile and the target can be mutually Coulomb excited, it is crucial to be able to discriminate between decay photons emitted by the

TABLE I. Detector geometries and the corresponding average Doppler shift $\langle E_{\rm lab}/E_{\rm c.m.}\rangle$ in the photon energy and $\langle \Omega_{\rm lab}/\Omega_{\rm c.m.}\rangle$ in the solid angle for photons emitted from the Bi projectile.

Setting	Blocks	Θ	Distance (m)	$\langle E_{\rm lab}/E_{\rm c.m.}\rangle$	$\langle \Omega_{\rm lab}/\Omega_{\rm c.m.}\rangle$
I	A–D	73.5°–120.5°	0.5	0.5	0.25
II	A,B	97°–123°	1.0	0.5	0.25
	C,D	18°–44°	1.0	2	4

target from those emitted by the projectile in order to reconstruct with confidence two-photon events originating from the decay of one nucleus. This discrimination is achieved by exploiting the large Doppler shift of γ rays emitted by the fast moving Bi projectile (see Table I). In contrast, γ rays from the Pb target are unshifted. However, this method does not discriminate the two-γ decay of the GDR2 state from two photons emitted by different target nuclei. From the calculated excitation cross sections (Table II) the target thickness was chosen ($\sqrt{2}\times 420$ mg/cm^2) such that this background was $\sim 5\%$ of the expected GDR2 yield.

Figure 1 shows the energy spectrum of single γ rays detected in TAPS geometry I for peripheral events defined as having no charged particle coincident in the FW. Three features dominate the spectrum. An exponential decrease below 10 MeV arises from the shape of the virtual photon spectrum and from statistical γ decay of excited reaction products. A slower exponential decrease above 20 MeV is related to incompletely suppressed central events and to one-step electromagnetic excitations into the quasideuteron region. In between, a large structure centered near 13 MeV is superimposed on the background from the other two processes. The peak position of this structure is independent of the observation angle, consistent with emission from a source at rest in the laboratory system (LS). We assign this structure to the γ decay of the GDR in the ^{208}Pb target. In this geometry, GDR γ rays from the Bi are Doppler shifted to ≈ 7 MeV (see Table I). The giant resonance peak is extracted by subtracting the background which is parametrized as the sum of two exponentials. The slopes of the exponentials are fixed by the data on each side of the GDR peak. The two intensities are allowed to freely vary as the data are fitted with a Lorentz on top of the background. The result after subtraction of the background is shown in the inset of Fig. 1 with the Lorentzian line shape fit. In this procedure the variation of the excitation probability over the resonance has been neglected.

TABLE II. Compilation of the resonance parameters of the Coulomb-excited GDR and GDR2 in the given nuclei.

Nucleus	Mode	E^* (MeV)	Γ (MeV)	$\sigma_{\rm exc}$ (b)	$\sigma_{\rm calc}$ (b)
^{208}Pb	GDR	13.3±0.1	4.1±0.1	4.9±0.4	5.1
^{208}Pb	(γ,n)[a]	13.42	4.02	...	...
^{209}Bi	GDR	13.1±0.2	4.2±0.2	5.0±0.5[b]	5.1
^{209}Bi	(γ,n)[c]	13.45	3.97	...	...
^{208}Pb	GDR2	25.6±0.9	5.8±1.1	0.77±0.22[d]	0.36

[a]See Ref. [19].

[b]Using $\sigma_{\gamma 0}$(Pb)/$\sigma_{\gamma 0}$(Bi)$\approx$ 1.3; see Ref. [22].

[c]See Ref. [21].

[d]Assuming the γ branching ratio (B) of the GDR2 is $B_{\rm GDR2} = B_{\rm GDR}$ [4].

The resonance parameters listed in Table II were extracted by unfolding the Lorentz fit with the detector response. Using methods described in Ref. [16], the detector response was determined for the TAPS detector modules by GEANT3 [17] calculations and compared with several electron and tagged photon measurements [13, 18]. The unfolding was performed by iteratively seeking an original Lorentz distribution that when folded with the detector response closely reproduced the fit to the data. The unfolding procedure increased the peak energy by ~ 0.5 MeV and decreased the width by $\sim 10\%$. The results agree very well with the parameters obtained from the ^{208}Pb(γ,n) reaction [19].

Further proof that the structure in Fig. 1 corresponds to the decay of the GDR in the ^{208}Pb target can be gathered from the γ angular distribution. Decay photons from the target must be symmetrically distributed

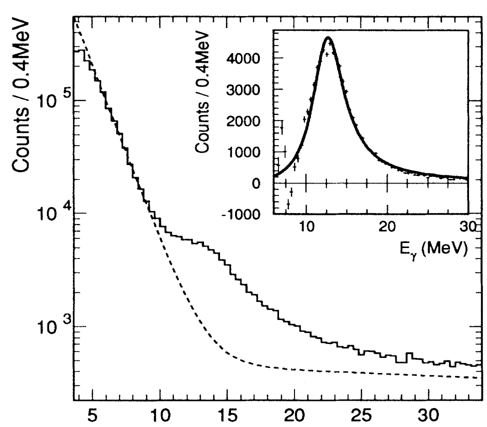

FIG. 1. Photon energy spectra measured in geometry I for peripheral events (solid histogram). The large structure around 13 MeV corresponds to the γ decay of the Coulomb-excited GDR in the ^{208}Pb target. The inset shows a Lorentz fit to the difference between the data and the background (dashed line) described in the text.

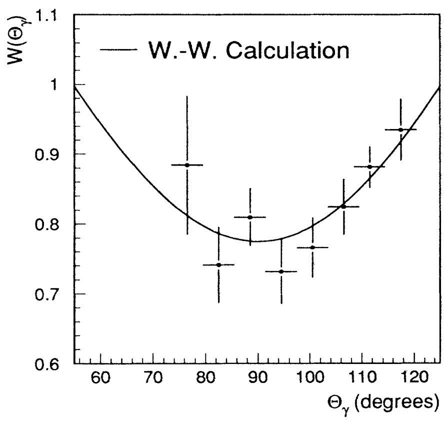

FIG. 2. Angular distribution of the GDR decay photons from the ^{208}Pb target. The solid curve is the prediction based on the model described in the text.

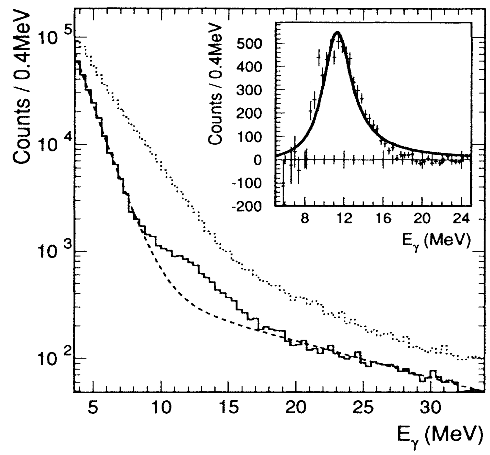

FIG. 3. Laboratory photon energy spectrum at forward angles (dotted line), after application of a Lorentz transformation into the frame of the moving Bi projectile (solid line). The inset shows a Lorentz fit to the difference between the data (solid line) and the background (dashed line) described in the text.

about 90° to the beam axis, whereas the decay photons from the projectile will be sharply peaked to forward angles. The symmetry of the observed angular distribution of the structure (Fig. 2) is in agreement with photon decay from the ^{208}Pb target. In contrast the background is peaked at forward angles. Furthermore, by using the Weizsäcker-Williams formalism one can calculate the expected relative population of the m substates for an $E1$ first-order excitation [9]. For the system 1A GeV ^{209}Bi + ^{208}Pb this method yields the ratio $(P_{m=+1} + P_{m=-1})/P_{m=0} \approx 28$ in the Pb target. This leads to an angular distribution $W(\theta_\gamma) = 1 + 0.45 P_2(\cos\theta_\gamma)$ (solid curve in Fig. 2) in good agreement with a fit to the data $1 + (0.54 \pm 0.11) P_2(\cos\theta_\gamma)$. Higher-order terms have not been considered because $E1$ γ decay will dominate all other multipolarities by at least 2 orders of magnitude [20] for these photon energies.

To further verify the discrimination between target and projectile excitations, the Coulomb-excited GDR in the ^{209}Bi projectile was studied with the detector geometry II, blocks C-D. Here, the LS γ energy spectrum shows no pronounced structure (dotted histogram in Fig. 3). The Lorentz boosted low energy component from the Bi projectile obscures the contribution from the Pb GDR. Since photons emitted from a moving source will have a different LS energy depending on the angle of the individual detector module, the peak position of the Bi GDR varies from 17 to 39 MeV over the angular range of the detectors. After a Lorentz transformation into the projectile rest frame, a distinct structure appears as shown by the solid histogram in Fig. 3. We assign this structure to the γ decay of the Coulomb-excited GDR in the ^{209}Bi projectile. The parameters obtained after unfolding (see Table II) are in agreement with those from the ^{209}Bi(γ, n) reaction [21].

Having established the relativistic Coulomb excitation of the GDR in both the projectile and target we now focus on the GDR2 in the ^{208}Pb target. For this measurement the detectors were returned to geometry I. A characteristic feature of a harmonic GDR2 mode is the emission of two nearly equal energy photons with a sum energy about twice that of the GDR. The spectrum shown in Fig. 4 is the sum energy of all coincident γ-γ pairs with no coincident particles in the FW and where the difference in the photon energies is less than 6 MeV. A broad structure above the continuum centered about 26 MeV is observed (and is absent if the difference energy window is shifted) which we ascribe to the

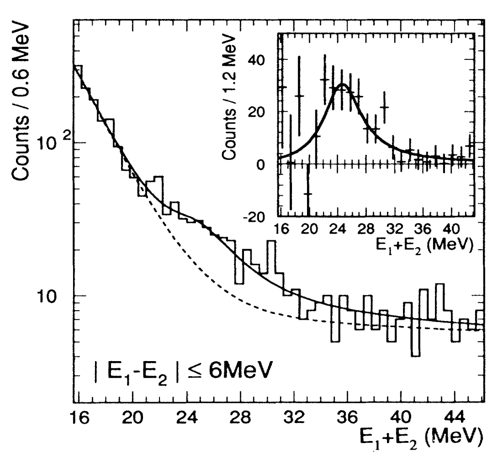

FIG. 4. Sum energy of coincident photon pairs with a difference less than 6 MeV for peripheral events. The large structure around 26 MeV is assigned to the two-γ decay of the GDR2. The inset shows a Lorentz fit to the difference between the data and the background (dashed line).

two-γ decay of the electromagnetically excited GDR2. After subtraction of the background denoted by the dotted line, the data are shown in the inset with a Lorentz fit. The resonance parameters, corrected for the detector response, are again listed in Table I. The measured ratio $E_{\rm GDR2}/E_{\rm GDR} = 1.93 \pm 0.07$ is in agreement with the value 2 expected from a harmonic oscillator model for the $T_<$ component ($T_z = 22$ for ^{208}Pb) of the GDR. Moreover, the ratio $\Gamma_{\rm GDR2}/\Gamma_{\rm GDR} = 1.4 \pm 0.3$ agrees with both the value 1.5 measured in π double-charge-exchange reactions [7] and the value 1.4 measured in the neutron decay measurement [10]. These results are in agreement with the width increase predicted by Landau damping [2] but disagree with other predictions [4, 5, 18]. The excitation cross section cannot be determined from this measurement since the branching ratio of the GDR2 for γ decay is not known. Under the assumption that the γ branching ratio for each phonon is independent of the number of phonons [4] ($\Gamma_\gamma/\Gamma_{\rm part} = 0.017$ in ^{208}Pb [20]), the excitation cross section is 770$\pm$220 mb. The above mentioned background of simultaneous excitation of the GDR in two target nuclei contributes less than 2.5% to the observed GDR2 yield. The GDR2 cross section is about a factor of 2 larger than the value of 360 mb obtained from Weizsäcker-Williams calculations. A similar enhancement in the GDR2 excitation has been observed in the neutron decay measurements [10, 12]. Finally we have compared the γ-γ angular correlation to predictions from the Weizsäcker-Williams model, assuming the two phonons are independently excited. Within the considerable statistical errors we find consistency with our data.

In conclusion, the first observation of the two-γ decay of the Coulomb-excited GDR2 in ^{208}Pb has been reported. The results imply that the two-phonon $T_<$ GDR is a harmonic excitation; moreover the width increases only by a factor of about $\sqrt{2}$ which is consistent with all other experimental data and the prediction by Landau damping but disagrees with other model predictions. This moderate increase in width is encouraging for further studies of states with even larger phonon numbers.

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