Electromagnetic Interaction in Energetic Heavy-Ion Collisions

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Abstract

We discuss the process of electromagnetic interaction between heavy ions in peripheral collisions at large relative velocities. Emphasis is paid to excitations of single and multi-phonon giant resonances. Results on the double isovector giant dipole resonance obtained at SIS are summarized.

1. INTRODUCTION

At bombarding energies around the Coulomb barrier the process of "Coulombexcitation" has been widely used in nuclear structure studies of low lying collective states. In deformed nuclei, multi-step excitations in ground-state rotational bands up to spins of $30\hbar$ were observed [1], thus involving a many-step excitation process. For a single-step excitation, however, the maximum excitation energy E_m which can be reached is limited to a few MeV, higher lying states such as giant resonances cannot be excited.

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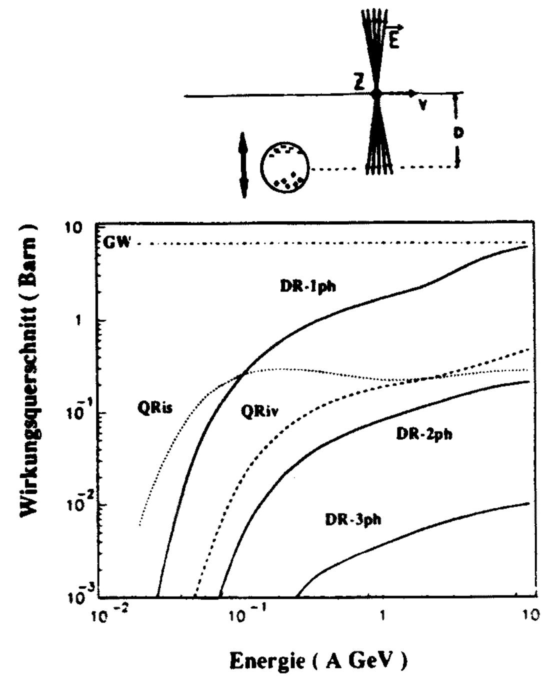

Fig. 1: Cross section estimates for the isovector giant dipole resonance and its two and three phonon states (solid lines) and for the isoscalar (dotted line) and isovector (dashed line) giant quadrupole resonance of ^{136}Xe. The cross sections are shown for collisions with Pb nuclei at various bombarding energies. For comparison, the geometrical cross sections is indicated (dashed-dotted line). On top of the figure, an illustration of the scattering process is given.

E_m is basically determined by the duration of the electromagnetic interaction, a rough estimate would be

$$E_m(MeV) = \hbar/t = \frac{200 \cdot \beta \cdot \gamma}{D(Fm)}$$

where β denotes the relative velocity in units of c, γ describes the relativistic time-dilatation and D the internuclear distance. The minimum value of D equals about the sum of the two nuclear radii of the collision partners, at lower values nuclear absorption obscures the process of electromagnetic interaction. With bombarding energies of ~ 1 A·GeV, i.e. $\beta \approx 0.86$ and $\gamma \approx 2$, now available at SIS in Darmstadt, therefore, giant resonances should be excited. In Fig. 1 we show predicted cross sections for the isovector giant dipole resonance (GDR) and for the giant quadrupole resonances of ^{136}Xe (GDR) in collisions with Pb nuclei (the parameters used in this calculation are presented below). For a theoretical description of such processes, Winther and Alder [2] used the semi-classical method and perturbation theory. Alternatively, the Weizsäcker-Williams method (WW) of virtual quanta can be applied which allows to incorporate experimental photo-absorption cross sections. It appears, that the high Fourier-components in the spectrum of virtual quanta, relevant for giant resonance excitation ($\hbar\omega = 10 - 30$ MeV), aquire sufficient strength to induce multi-step excitations. Due to Lorentz Contraction, the electromagnetic field in relativistic heavy ion collisions is predominantly of transversal character (see Fig. 1) and thus dipole moments are likely to be induced. It thus can be understood that the giant dipole resonance appears with the highest cross section, and even for its multi-phonon states relatively large cross section are predicted (Fig. 1). The coupled channel problem arising for multi-step excitations of the higher-phonon states can be solved analytically if these states are described in the harmonic oscillator model [3]. First, but indirect information on giant resonance excitation in relativistic heavy-ion collisions came from systematic radiochemical measurements [4,5] of one-neutron removal cross sections; in heavy nuclei giant resonances decay predominantly via neutron emission.

Direct evidence for higher order excitations, more precisely for the double isovector giant dipole resonance (DGDR), was obtained in recent experiments at the SIS facility, which will be reviewed in the following section. Emphasis is put on a first, fully exclusive DGDR measurement for ^{136}Xe performed by the LAND collaboration [6]. Observations of the DGDR were first reported from (π^+, π^-) double-charge-exchange reactions at LAMPF [7], the results of which will be included in the discussion.

2. EXPERIMENTAL METHODS AND RESULTS FOR THE DGDR

A fully exclusive measurement for a medium mass nucleus, ^{136}Xe, was carried out by the LAND collaboration, resulting in clear evidence for the electromagnetic DGDR excitation [6].

The experiment was performed at the heavy ion synchrotron (SIS) facility at GSI, Darmstadt. ^{136}Xe projectiles of 0.7 A ·GeV were used with a typical beam intensity of 10^4 particles per second, impinging on lead and carbon targets. The experimental setup is shown in Fig. 2. It meets the conjecture that the ^{136}Xe projectile, excited in a peripheral collision, de-excites by emission of neutrons and subsequent gamma decay of the heavy residue. 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. 2, the trajectories of the projectiles and of the projectile fragments were traced by means of four plastic scintillation counters, these detectors delivered position information in both dimensions perpendicular to the beam axis and also provided an excellent time of flight resolution. Beam fragments as well as non-interacting projectiles entered the dipole magnet ALADIN which had a large rectangular gap, 1.6 m 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 multi-sampling ionization chamber and a glass Cherenkov counter. 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 on the fragment momentum.

For the neutron measurement, the Large Area Neutron Detector (LAND) with high detection efficiency and multiple-hit capability was used [8]. The essential feature of accurate position and TOF information is achieved by modularizing the detector into 200 elements, allowing for a precise determination of the neutron momenta. A schematical view of the LAND device is shown in Fig. 3 and some of its performed parameters are quoted in Tab. 1.

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. Technical details are found in Ref. 6. Fig. 4 shows the resulting excitation energy spectrum for ^{136}Xe obtained with the Pb and C targets.

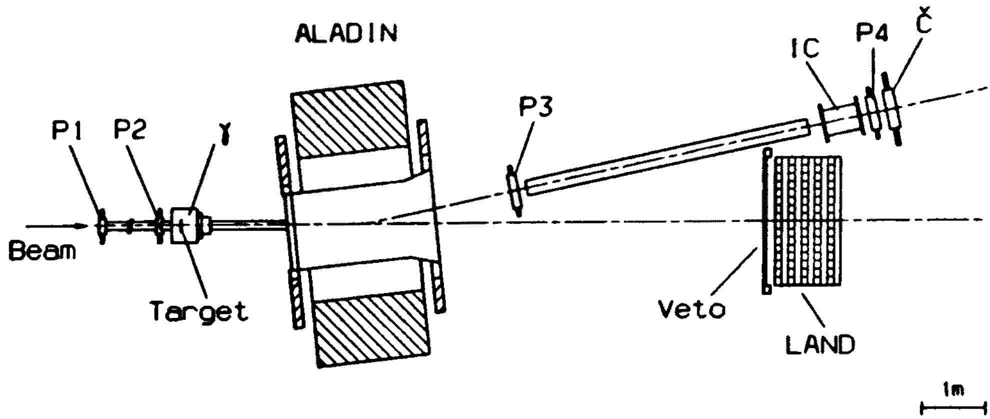

Fig. 2: Schematic view of the experimental set-up [6]. Shown are the beam and fragment tracking counters (P1-P4), the ionization chamber (IC), the Cherenkov detector (C), the dipole magnet (ALADIN), the gamma detector array (γ), the neutron detector (LAND, Veto) and parts of the beamline.

The experimental results are compared to calculations of the electromagnetic excitation within the framework of the Weizsäcker-Williams method (WW) of virtual quanta. The basic ingredients of such a calculation are the dipole and quadrupole photo-absorption cross sections; higher multipolarities can be neglected because of their expected low cross section. For the giant dipole resonance (GDR) the total photo-absorption cross section was extracted from the systematics summarized in Ref. 8, giving a resonance energy of 15.2 MeV and a width of 4.8 MeV (if approximated by a Lorentzian distribution). For the giant quadrupole resonances (GDR) parameters were obtained from the systematics presented in Ref. 9, resulting in a resonance energy of 12.3 ± 0.5 MeV, a width of 4.0 ± 0.5 MeV and a strength corresponding to 70 ± 20% of the energy-weighted sum rule (EWSR) for the isoscalar part (IS). For the isovector part (IV), a resonance energy of 24 ± 2 MeV, a width of 7 ± 2 MeV and 80 ± 20% EWSR strength was assumed; it should be noted, however, that the available systematics is rather poor for the isovector resonance. The quoted errors reflect the uncertainties to which the values can be extracted from the available systematics.

Tab. 1: Performance parameters of LAND, valid for neutron energies $\gtrsim$300 MeV

Parameter	Value
Efficiency	$\gtrsim$90%
Time-of-flight resolution	$\sigma_b \approx 300$ ps
Positional resolution	$\sigma_x \approx 3$ cm

The total energy integrated cross sections obtained from lead and carbon targets (Fig. 4) are 1.85 ± 0.1 and 0.07 ± 0.01 barn, respectively; the quoted errors include estimates of systematic effects. The WW calculation results in 0.03 barn for the carbon target. By adopting a scaling of the nuclear cross section with the target radius (see Ref. 5), it can be deduced 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. In Fig. 4 the excitation energy spectrum obtained for the Pb target is compared with the result of a WW calculation. This calculation takes into account single-step excitations only, it is based on the giant resonance parameters as discussed above. The resulting excitation energy distribution reproduces quite well the measured spectrum for the lead target up to excitation energies $E^* \lesssim 25$ MeV. A small discrepancy is observed around $E^* \approx 22$ MeV. However, the poor systematics of the isovector GQR would allow a shift in its resonance energy to this value, resulting in a better agreement.

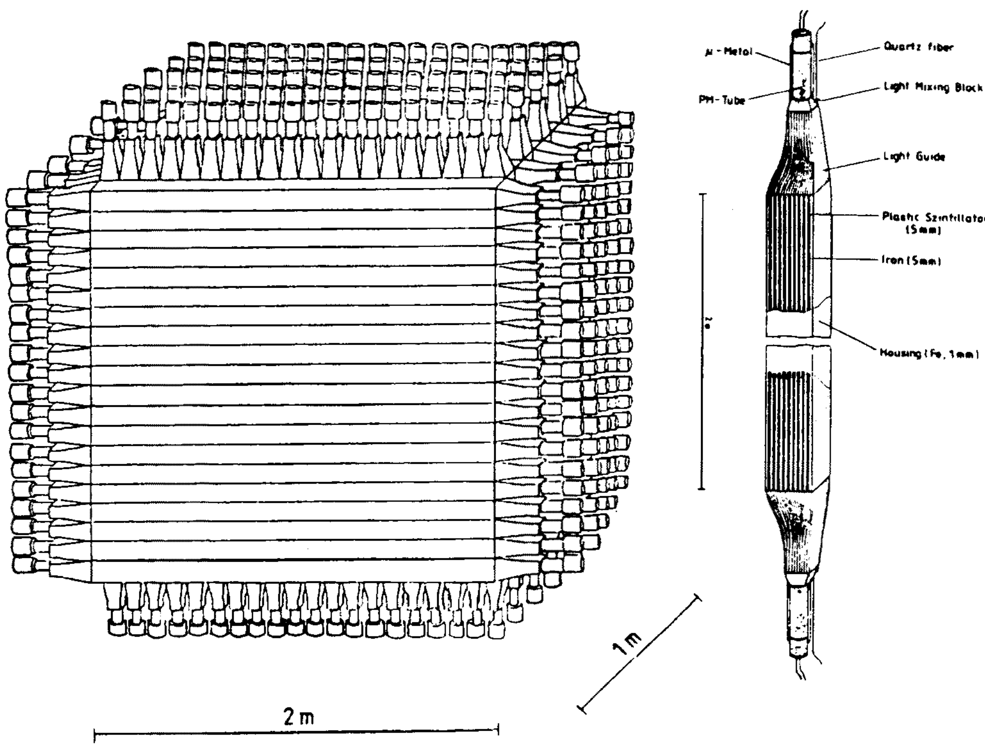

Fig. 3: Schematic view of the large Area Neutron Detector (LAND) and one of its subelements at GSI.

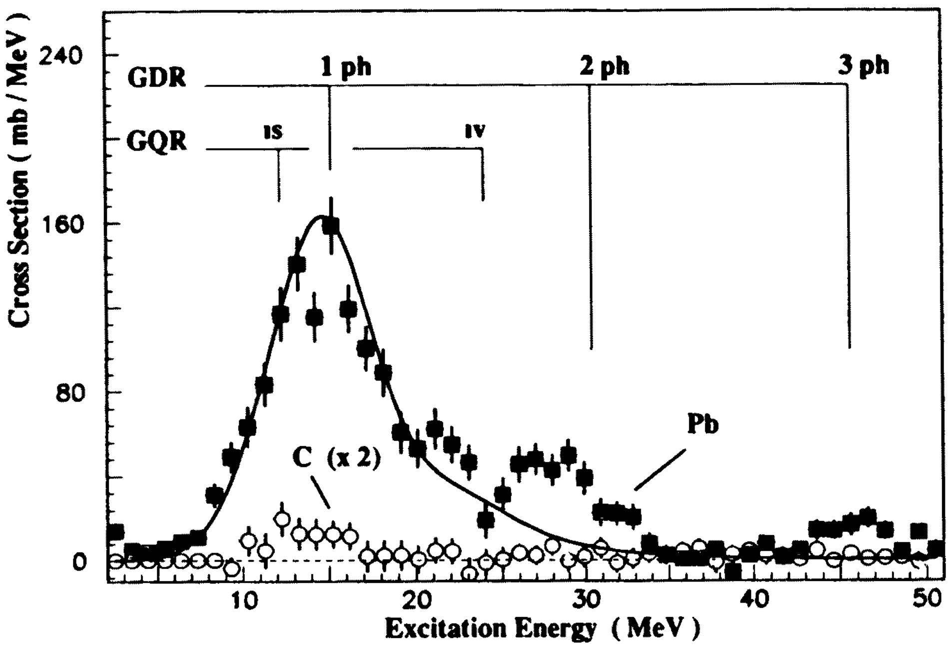

Fig. 4: Experimental results for ^{136}Xe projectile excitation using a Pb target (squares) and a C target (circles) and 0.7 A · GeV bombarding energy (from Ref. 6). The spectrum for the C target is multiplied by a factor 2 for better presentation. The expected resonance energies for the giant dipole and quadrupole resonances are indicated. For the multi-phonon (n ph) GDR's the values in the harmonic oscillator limit are used. The solid curve reflects the result of a first order WW calculation as outlined in the text.

As seen in Fig. 4, above 25 MeV a prominent structure is observed for the Pb target, which is centered slightly below twice the excitation energy of the GDR. This structure was assigned unambigously to the double giant dipole resonance (see Ref. 6 for details). A mean excitation energy of 28 ± 1 MeV, a width of 6 ± 2 MeV and the considerable cross section of 175 ± 50 mb was determined; these values will be discussed in section 3. From a WW calculation a cross section for the DGDR of about 110 mb is expected and thus a slight enhancement seems to be indicated. Another small structure appears around 45 MeV excitation energy, i.e. around the expected excitation energy of the three-phonon GDR, however, as discussed in Ref. 6 it might be caused by instrumental effects.

A different technique was used by W. Kühn and his coworkers of the TAPS collaboration, investigating the DGDR in ^{208}Pb [11]. It relies on the small direct γ-decay branch (~1%) of the giant dipole resonance. Single γ-ray spectra and γ-γ coincidences were recorded using the Two Arm Photon Spectrometer (TAPS) which consists out of 256 BaF_2 scintillation counters. ^{208}Pb targets were bombarded with ^{209}Bi projectiles of 1 A·GeV energy. Peripheral collisions were selected by suppressing reactions involving charged particle emission by means of a large, forward plastic wall.

The resulting single γ-ray spectrum is shown in Fig. 5; the γ-decay of the giant dipole resonance superposes a background formed by statistical γ-rays and bremsstrahlung at the expected γ-ray energy of ~13 MeV. Its cross section amounts to 5.0±0.4 barn. The γ-γ coincidence data were analyzed under the constraint that their energy difference is smaller than 6 MeV. The resulting γ-sum energy spectrum is also shown in Fig. 5. A structure evolves at a sum energy of ~25 MeV, which was assigned to the double γ-decay of the DGDR in ^{208}Pb; a mean energy of 25.6±0.9 MeV and a width of 5.8±1.1 MeV was deduced for the DGDR.

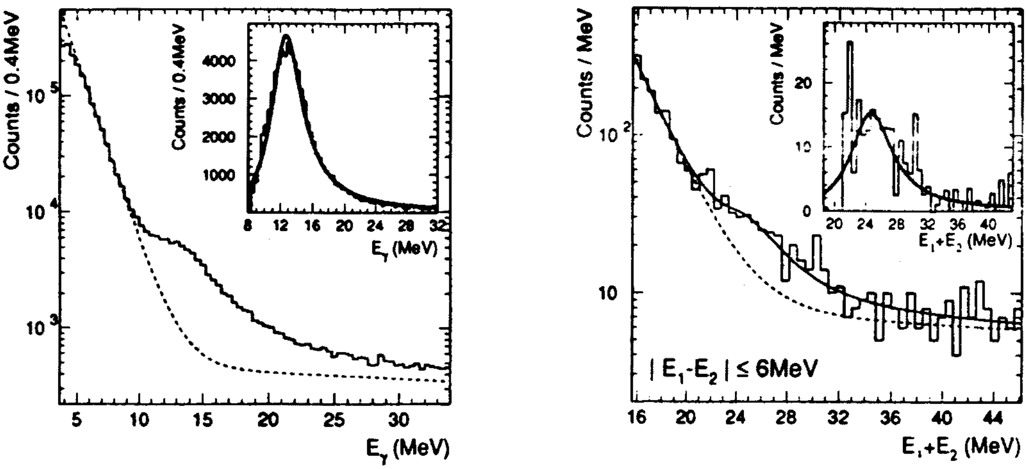

Fig. 5 (left): Single γ-ray spectrum obtained for the system ^{209}Bi (1 A·GeV) + ^{208}Pb. The inset shows the same spectrum after background (dashed line) subtraction.
(right): γ-ray sum-energy spectrum for the same system. The inset shows this spectrum after background subtraction. The data are taken from Ref. 11.

At LAMPF, a number of nuclei was investigated with pion double-charge-exchange reactions [7]. A structure appears at a Q-value around ~50 MeV, nearly independent of the investigated nucleus, which has been assigned to the DGDR. Empirical Coulomb energy corrections and isospin splitting must be taken into account in order to obtain the resonance energy. These corrections are in the order of 50% of the measured Q-value. For heavy nuclei (^{138}Ba, ^{197}Au) total cross sections of 20-40 μb were found, thus being four orders of magnitude smaller in comparison to the cross sections obtained with heavy ions.

Tab. 2: Summary of DGDR parameters for nuclei with A>100 as obtained from electromagnetic excitation with heavy ions (HI) or pion double charge-exchange (π). Mean energy E and width Γ are quoted relative to that of the GDR.

Nucleus	Probe	Ref.	E(DGDR)/E(GDR)	Γ(DGDR)/Γ(GDR)	Cross Section
^{136}Xe	HI	[6]	1.84 ±0.06	1.3±0.4	175±50mb
^{208}Pb	HI	[13]	1.93±0.07	1.43±0.27	-
^{138}Ba	π	[7]	~2.0	1.7±0.5	24 μb
^{197}Au	π	[7]	~1.6	2.4±0.5	41 μb.

In Table 2 the DGDR data for heavier nuclei (A > 100) are summarized as far as presently available. We quote the observed cross sections and the mean energy E and width Γ of the resonance relative to the corresponding values of the GDR. In the model of a harmonic oscillator one would expect [3]:

$$E(DGDR)/E(GDR) = 2 \quad \text{and} \quad \Gamma(DGDR)/\Gamma(GDR) = 2$$

It appears that, with the possible exception of ^{197}Au, the harmonic approximation works well with regard to excitation energy, the width of the DGDR, however, seems to be significantly smaller than expected. Thus the somewhat puzzling result emerges, that for the DGDR the damping, relative to the frequency, proceeds less fast than for the single dipole giant resonance.

4. OUTLOOK

For the first time, the dominant role of the electromagnetic excitation of giant resonances in peripheral, relativistic heavy ion collisions could be established in exclusive experiments. In particular, clear evidence for the excitation of two-phonon giant dipole resonances were obtained and considerable cross sections (> 100 mb) were found. This, together with the observation of a relatively narrow width, gives hope that in near future even higher-phonon states may be observed. Nevertheless, these experiments need further refinements and more systematic work, before reaction mechanism and nuclear structure of this new class of giant resonances will be fully understood. For example, a measurement of differential cross sections would be desirable, which is difficult, because of the extremely low momentum transfer in such reactions. Cooled beams of very low emittance, as in principle can be delivered by the storage ring ESR at GSI, might give access to such experiments. Another very interesting subject would be the investigation of giant resonances in radioactive nuclei with extreme N/Z ratio. First experiments in this direction were carried out using secondary beams produced by means of the FRS at GSI, only very preliminary data, however, are available so far.

ACKNOWLEDGEMENT

We thank W. Kühn, V. Metag, J. Ritmann and the TAPS collaboration for discussions and the permission to include their recent work in this article.

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