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COULOMB FRAGMENTATION AND COULOMB FISSION OF RELATIVISTIC HEAVY-IONS AND RELATED NUCLEAR STRUCTURE ASPECTS * **

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The Coulomb excitation of ^{208}Pb projectiles has been studied at an energy of 640 A MeV. Cross sections for the excitation of the two-phonon giant dipole resonance were measured for different targets, and show clear evidence for a two-step electromagnetic excitation mechanism. The experimental cross sections exceed those calculated in the harmonic oscillator approximation by a factor of 1.33 ± 0.16. The deduced 2γ-decay probability is consistent with the expectation in the harmonic limit. Finally, the excitation of the two-phonon giant dipole resonance in the deformed and fissile nucleus ^{238}U is discussed.

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1. Introduction

If the picture of giant resonances as a collective harmonic vibration of the nucleons is valid, the excitation of the second oscillator quantum should be possible. Indications for the excitation of this new class of giant resonances were first seen in (π^+,π^-) double charge exchange reactions [1], were a structure was observed at twice the energy of the giant dipole resonance (GDR). Evidence for the excitation of the two-phonon giant quadrupole resonance in inelastic heavy-ion scattering experiments was also reported [2]. In the last years several experiments were performed aimed at studying the double giant dipole resonance (DGDR) by using relativistic Coulomb excitation [3]. Coulomb excitation at high energies (0.5 to 1 A GeV) is a very effective method to excite the DGDR because of the high excitation probability: approximately 0.3 for the GDR in the heaviest systems in a grazing collision. This leads to a high probability for a two-step process and, thus, to cross sections of several hundreds of millibarns for the excitation of the two-phonon state of the GDR. This allows for a detailed study of this high lying collective excitation mode. The most surprising results of the Coulomb excitation experiments were the observed cross section enhancement by a factor of two to three found for ^{197}Au [4] and ^{136}Xe [5], respectively, and the relatively small width of the DGDR, which turned out to be only about 1.5 times the width of the GDR [5, 6].

Since the dominant decay channel of giant resonances in heavy nuclei is neutron evaporation, most of the experiments have investigated the neutron decay, either by measuring inclusive xn - cross sections [4, 7] or by detecting all decay products after projectile excitation in an exclusive measurement as performed by the LAND group [5, 8]. In section 2 of this paper we present the results of such an experiment where the Coulomb excitation of the DGDR in ^{208}Pb projectiles on different targets has been investigated. Coulomb excitation of the DGDR in ^{208}Pb was already observed by other groups [6, 9] by making use of the small direct γ-decay branch (~2% for the GDR in Pb). By comparing our results obtained for the n-decay of the DGDR with the results for the two-γ decay of the DGDR measured by Ritman *et al.* [6] we can obtain the branching ratio for the γ decay of the DGDR.

For fissile nuclei such as ^{238}U fission becomes an important decay channel of giant resonances as well. For ^{238}U there is evidence for DGDR excitation from inclusive xn - cross sections [7]. Coulomb fission was studied in several experiments at GSI [10–12]. While the fission cross section is not sensitive to the DGDR excitation, one can obtain information on the excitation energy distribution indirectly, from the charge distribution of the fission fragments as shown in [11]. Recently, we have performed an experiment to investigate Coulomb excitation of ^{238}U projectiles at an energy of 500 A MeV. The kinematically complete measurement of the decay products allows for a reconstruction of the excitation energy not only for the neutron decay channels but also for the fission channel.

2. Coulomb excitation of the DGDR in ^{208}Pb

2.1. Experimental method

The experimental procedure consists of projectile excitation and a detection of all outgoing decay products, namely projectile fragments, neutrons, and γ-rays originating from excited fragments. The excitation energy E^* of the ^{208}Pb projectiles can be then reconstructed by analyzing the invariant mass $M^2 = (\sum_i P_i)^2 = (M_P + E^*)^2$, where P_i are the 4-momenta of the dissociation products and M_P the projectile rest mass. To a good approximation, the energy released by γ-rays from excited fragments can be separated in the analysis and added to the invariant mass calculated by using ground state masses. The experimental method is described in more detail in [3, 5, 13, 14].

The ^{208}Pb beam delivered by the SIS synchrotron at GSI with an energy of 640 A MeV was directed onto targets of C, Sn, Ho, Pb, and U. The neutrons from the decay of excited states in the projectile are kinematically focussed to forward angles and were detected by the LAND neutron detector [15] placed under zero degree about 11 m downstream from the target. The solid angle covered by the 2×2 m^2 large detector is sufficient to detect the neutrons with momenta of interest with an efficiency of more than 90 %. Momenta of the neutrons were obtained from the position and the time-of-flight information. The granularity of the LAND detector (200 submodules) allows also for the determination of the momenta, if more than one neutron hits the detector. The procedure of resolving multiple hits is described in [14].

The fragments were deflected by a large dipole magnet, their momentum and nuclear charge Z_{F} was determined by plastic scintillators for the time-of-flight measurement, by position measurements with wire chambers, and by the energy loss information from an ionisation chamber. Coulomb excitation of giant resonances was selected experimentally by requiring a fragment with $Z_{\mathrm{F}} = 82$ in coincidence with the LAND neutron detector. The γ-rays emitted from excited fragments were detected with an array of 66 BaF$_2$ crystals arranged in forward hemisphere around the target.

2.2. Results and discussion

From the invariant mass analysis the differential cross section distribution $d\sigma/dE^*$ for Coulomb excitation and decay into the $1n$ to $3n$ channels were obtained (higher neutron multiplicities are negligible). Therefore the data were corrected for nuclear contributions by using the results for the C target and a scaling procedure as well as for background from reactions outside the target by using a measurement without target. After applying corrections for finite solid angle acceptances and detector efficiencies the cross section distributions shown in Fig. 1 are obtained.

The results for the Pb target are shown in the middle panel of Fig. 1 and for the Sn target in the lower part. Both spectra show the dominant structure of the GDR at an energy of about 10 MeV. The peak is shifted to lower excitation energies compared to the known position of the GDR, as one can see by comparison with the upper part of the figure, where a calculation with the known parameters of the GDR in ^{208}Pb is shown. This shift is mainly connected with an incomplete measurement of the total γ-ray energy emerging from excited fragments after neutron evaporation. After applying an experimental filter based on Monte Carlo simulations and an experimentally determined detector response of the LAND [14], the calculated curve fits almost perfectly the data (solid line in Fig. 1).

To extract the parameters for the DGDR the data were compared to a calculation using strength distributions of the GDR (dashed line in Fig. 1) and of quadrupole excitations (dotted curve in Fig. 1) known from the literature [16–18]. The absolute magnitude of the single phonon excitations were allowed to vary for every target. The DGDR contribution was parametrized by a Gaussian distribution. In a least-squares minimization, the width, mean energy, and magnitude of the DGDR cross section distribution were determined. In order to reduce the number of free parameters, the width and the mean energy were constrained to be the same for all targets (Sn, Ho, 2×Pb, U). The calculations of the Coulomb excitation cross sections were done with the semi-classical method [19–21]. As mentioned above, prior to comparison with the experimental data, the calculation had to pass the experimental filter.

As a result of the fitting procedure described above, we obtain for the one phonon excitation a renormalization factor of 1.01±0.02, averaged over the measurements with different targets, thus consistent with unity. The good agreement with the semi-classical calculation can also be seen in Fig. 2, where the integrated cross sections for one and two-phonon excitations are compared to the calculated ones, plotted as a function of target nuclear charge Z_T. An input quantity to the semi-classical calculation is the minimum impact parameter for which Coulomb excitation breaks down suddenly

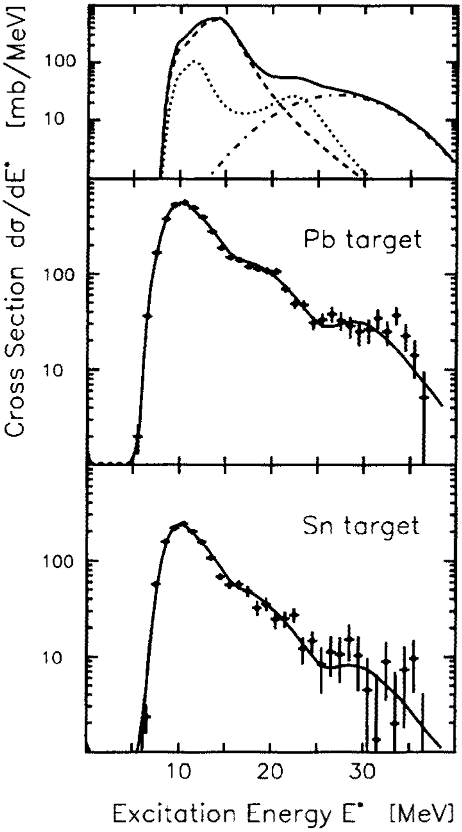

Fig. 1. Differential cross sections $d\sigma/dE^*$ for electromagnetic excitation of ^{208}Pb at 640 A MeV on a Pb target. Top: Calculation using known parameters for single GDR (dashed curve) and isoscalar plus isovector quadrupole excitations (dotted curve). The cross section for the DGDR indicated by the dot-dashed curve results from a fit to the data (see text). Middle: Experimental cross section $d\sigma/dE^*$ for the Pb target compared to the calculation shown above after applying the experimental filter. Bottom: same as in the middle panel but for the Sn target.

in favour of nuclear processes. We use the parametrization given in [22], which was shown to reproduce best the xn cross sections for Coulomb excitation of ^{197}Au [23]. The fact that we can reproduce the measured 1-phonon cross sections essentially without any free parameters gives confidence in the procedure of the analysis. In contrast to the one-phonon contributions, we find for the integrated DGDR cross sections an enhancement by a factor

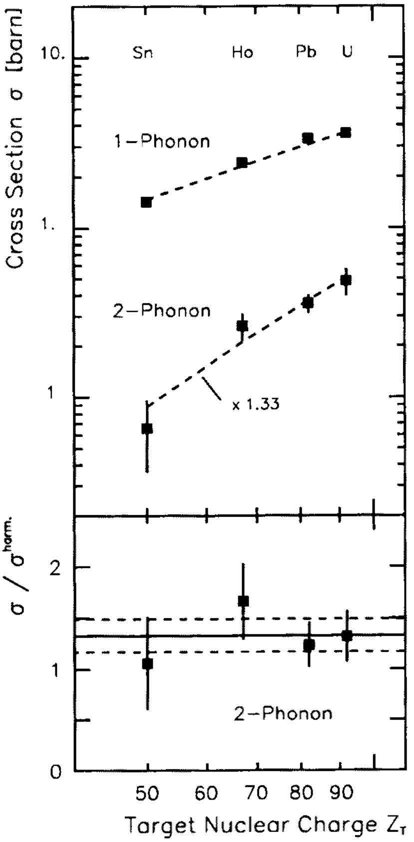

Fig. 2. Top: Comparison of the integrated experimental (symbols) and calculated (dashed lines) cross sections for one and two-phonon excitations of the GDR in ^{208}Pb for different targets; in case of the DGDR the calculated values are multiplied by a factor of 1.33. Bottom: Ratio of experimental cross sections for DGDR excitation to the cross sections calculated in the harmonic approximation (see text). The solid and dashed lines represent the mean value and its error, respectively.

of 1.33±0.16 relative to the calculation in the harmonic approach. This is shown in the lower part of Fig. 2, where the ratio of experimental to theoretical cross sections is shown for the different targets. The averaged value together with its error is indicated by the solid and dashed lines, respectively. In contrast to earlier observations for other nuclei [4, 5], the cross sections deviate only slightly from the semi-classical calculation. In Ref. [24] this enhancement is discussed in terms of anharmonicities. The authors obtain an increase of 10% in DGDR cross section for our system if anharmonicities and nonlinearities of the external field are taken into account, which could even be higher if the configuration space would not be truncated [24, 25]. Such anharmonicity effects are expected to be more pronounced in open shell nuclei and, thus, may explain the different cross section enhancement factors observed experimentally.

One of the most important results is the Z_T dependence of the DGDR cross section shown in Fig. 2. As can be seen in the double logarithmic scale of Fig. 2, the slope of the two-phonon cross section is steeper than for the 1-phonon excitation. For the ratio of the slopes for 2-phonon to 1-phonon cross section dependances we obtain 1.8 ± 0.3 consistent with the expectation of a value of 2 for a two-step electromagnetic excitation. Thus, we have shown, that the structure observed in the excitation spectrum at about twice the energy of the GDR, which was assigned to be the two-phonon excitation of the GDR, originates indeed from a two-step electromagnetic excitation process.

From the fitting procedure to our data we also obtain the width and the mean energy of the DGDR. The weighted mean of our results and the values given in [6] are 6.3 ± 1.3 MeV and 26.5±0.8 MeV, respectively. In Fig. 3 these values are compared to the harmonic oscillator model by using

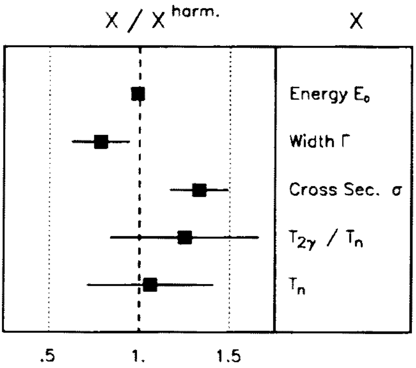

Fig. 3. Ratio of various experimental results X for the DGDR excited in ^{208}Pb to the respective quantities X^{harm} expected in the harmonic limit. Compared are the peak energy E_0, the width Γ, the integrated cross sections σ averaged over all targets, as well as the branching ratio $T_{2\gamma}/T_n$.

the folding procedure [21], which predict the width and mean energy to be about twice the respective values of the GDR. As can be seen from Fig. 3, where the ratios of the experimental results to the theoretical predictions are shown for various quantities, the mean energy is consistent with the expectation of $2 \times E_{\rm GDR}$, whereas the measured width is significantly lower than $2 \times \Gamma_{\rm GDR}$.

By combining the results of our experimental measurement of the cross section for the n-decay channels with the results of Ritman *et al.* [6] for the cross sections of the γ decay of the GDR and the 2-γ decay of the DGDR, we determine the branching ratios for these channels to be $(1.9 \pm 0.2) \times 10^{-2}$ and $(4.5 \pm 1.5) \times 10^{-4}$, respectively. The result for the GDR is consistent with the experimental value of 0.017 given in [26]. In the picture of a harmonic oscillator with two independently decaying phonons the branching ratio for the 2γ decay is expected to be $\Gamma_{2\gamma}^{\rm DGDR}/\Gamma_n^{\rm DGDR} = (\Gamma_\gamma^{\rm GDR}/\Gamma_n^{\rm GDR})^2$. The ratio of the experimental finding to this prediction is 1.25 ± 0.40 corroborating the picture of two non-interacting phonons.

3. Coulomb excitation of ^{238}U

With a similar experimental method as used for the Pb-experiment described in the last section we have measured the Coulomb excitation of the deformed and fissile nucleus ^{238}U at a beam energy of 500 A MeV. The setup was modified to make it suitable for the measurement of the momenta of both fission fragments in coincidence.

In previous experiments, inclusive cross sections were measured for the neutron channels [7] and for the fission channel [10–12]. The $3n$ cross sections show a strong Z_T dependence which reflects the excitation of the DGDR. The cross sections can be explained quantitatively by a semiclassical calculation; no cross section enhancement for DGDR excitation was observed. The fission cross sections are not sensitive to the excitation of the two-phonon GDR. The charge distribution of fission fragments, however, supply an indirect access to the excitation energy. From two experiments performed at GSI, peak to valley ratios of 7.1 ± 1 [11] and 7.2 ± 1 [12] were extracted for Coulomb fission of ^{238}U at 750 A MeV using a Pb target and at 1 A GeV using a U target, respectively. This is in contrast to the peak to valley ratio of 50 expected for fission at an excitation energy of the GDR. The filling of the valley can be to a large extend attributed to DGDR excitation. Using the excitation energy dependence of the peak to valley ratio from literature, a cross section of 143 ± 20 mb for symmetric fission was calculated [11]. This corresponds to a peak to valley ratio of 9.7 ± 1.5, which is in much better agreement with the experimental value. One might tend to interpretate the remaining discrepancy as a higher than calculated cross section for the DGDR contribution.

A better access to the excitation energy of the fissioning system can be obtained by detecting the neutron multiplicity. By measuring, in addition, the four-momenta of the neutrons and of the fission fragments one can determine the excitation energy in a similar analysis as described above for the xn channels. Since the data evaluation of the Uranium-experiment is still at the beginning, this type of analysis is not yet done. However, the dependence of the charge distribution of the fission fragments on the excitation energy can be seen by plotting this distribution as a function of the LAND hit multiplicity. The preliminary data are shown in Fig. 4 for fission of 500 A MeV ^{238}U projectiles impinging on a Pb target. In order to enhance the contribution from Coulomb excitation only those events, for which the sum of the two fragment charges was appr. 92, were taken into account. One clearly sees the asymmetric fission at low hit multiplicities in the range from 1 to 15, i.e. up to about 5 neutrons observed. The maximum of intensity appears around hit multiplicity 9, which corresponds to an average neutron multiplicity of about 3. From photoabsorption data [27] it is known that the mean number of neutrons evaporated from fission fragments is about 3.2 at an excitation energy of 11 MeV. The maximum of the calculated Coulomb excitation cross section distribution $d\sigma/dE^*$ for 500 A MeV ^{238}U + Pb is located at 11 MeV in agreement with the estimate given above.

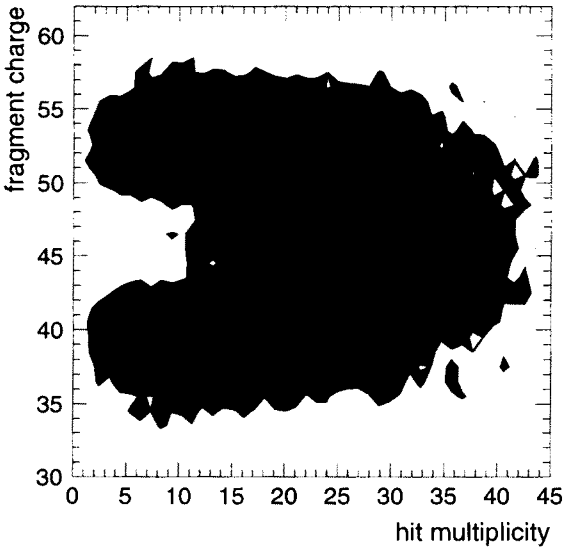

Fig. 4. Nuclear charge distribution of fission fragments in the reaction ^{238}U + Pb as a function of the hit multiplicity of the neutron detector. The mean hit multiplicity for one neutron is about 2.8. In order to reduce the nuclear contribution the measured sum of the fragment charges was required to be 92. The transition from asymmetric to symmetric fission with increasing neutron multiplicity is clearly visible.

For higher multiplicities the contribution from symmetric fission becomes more important and dominates for hit multiplicities larger than 20. The contributions from high excitation energies originate mainly from fission after nuclear reactions, which can be suppressed even more effectively in the final analysis. The remaining contribution will then be subtracted by using the results obtained with the C target.

4. Summary and outlook

The Coulomb excitation of ^{208}Pb was studied at a beam energy of 640 A MeV using different targets. Cross sections were derived for one-phonon excitations of the GDR and giant quadrupole resonances, as well as for the excitation of the two-phonon state of the GDR. The cross sections for one-phonon contributions as well as the mean energy and width of the GDR agree very well with a semiclassical calculation, which uses parameters for the giant resonances from the literature. For the DGDR we obtain a slightly larger cross section than calculated in the harmonic oscillator approach by a factor of 1.33 ± 0.16. The Z_T dependence of the DGDR cross section shows the behavior expected for a two-step electromagnetic excitation. As already observed in the earlier experiments, the width of the DGDR is smaller than the expected value of two times the width of the GDR, while the mean energy is about twice the energy of the GDR, consistent with the harmonic approach. In addition, the branching ratio for the 2γ decay of the DGDR was extracted to be $(4.5 \pm 1.5) \times 10^{-4}$, which is within the error in agreement with the harmonic picture of two independent non-interacting phonons.

Two new experiments to study the excitation of the DGDR were carried out recently by our group, which are presently being analysed. An improved experimental setup was used to measure differential cross sections with respect to scattering angle for the Coulomb excitation of 700 A MeV ^{136}Xe projectiles. The different impact parameter dependances of one-step and two-step excitation processes can be used to disentangle their contribution to the total cross section. The second experiment aims at the excitation of the DGDR in a deformed nucleus, where the strength distribution is expected to split into three components. Up to now there are only inclusive experiments for measuring xn cross sections and charge distributions of fission fragments after Coulomb excitation of ^{238}U; from both experiments there is evidence for DGDR excitation. We have used a ^{238}U beam at an energy of 500 A MeV. The experimental setup was modified in such a way, that, in addition to the xn channels, the fission channel can be investigated. The charge distribution of the fission fragments as a function of the hit multiplicity of the LAND neutron detector shows the transition from asymmetric fission, dominant at low excitation energies, to symmetric charge distributions at higher excitation energies. In the further analysis we want to obtain the cross section distribution $d\sigma/dE^*$ for the xn and fission channels after Coulomb excitation, which includes the Γ_n/Γ_f ratio as a function of excitation energy, in particular for the DGDR decay.

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