Measurement of the Cross Section for Electromagnetic Dissociation with Neutron Emission in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV

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The first measurement of neutron emission in electromagnetic dissociation of ^{208}Pb nuclei at the LHC is presented. The measurement is performed using the neutron zero degree calorimeters of the ALICE experiment, which detect neutral particles close to beam rapidity. The measured cross sections of single and mutual electromagnetic dissociation of Pb nuclei at $\sqrt{s_{NN}} = 2.76$ TeV with neutron emission are $\sigma_{singleEMD} = 187.4 \pm 0.2(stat)^{+13.2}_{-11.2}(syst)$ b and $\sigma_{mutualEMD} = 5.7 \pm 0.1(stat) \pm 0.4(syst)$ b, respectively. The experimental results are compared to the predictions from a relativistic electromagnetic dissociation model.

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When two interacting nuclei collide at an impact parameter larger than the sum of the nuclear radii the interaction is purely electromagnetic. The electromagnetic field of one of the two ions is experienced by the other ion as a flux of virtual photons. The equivalent photon method, proposed by Fermi [1] in order to treat the moving electromagnetic field of a charged particle, was later extended by Weizsäcker and Williams to collisions of ultrarelativistic electrons and protons with nuclei [2,3]. As beam energy increases, the photon spectrum hardens and the flux is enhanced, due to the increase of the Lorentz contraction of the Coulomb field. Moreover the photon flux is proportional to Z^2, with Z the charge number of the emitting nucleus. Therefore the electromagnetic interactions become dominant in ultrarelativistic collisions of heavy ions. Two processes, the bound-free pair production and the electromagnetic dissociation (EMD), have attracted special attention in recent years, because they provide stringent limits on the beam lifetime in heavy-ion colliders [4]. As predicted [5], the process of excitation and subsequent decay of the giant dipole resonance (GDR) via emission of one or two neutrons from colliding Pb nuclei occurs in ~60% of EMD events at the LHC. This can be exploited to measure the luminosity at heavy-ion colliders by detecting forward neutrons [6].

This Letter reports the first measurement of the electromagnetic dissociation cross section of ^{208}Pb nuclei at $\sqrt{s_{NN}} = 2.76$ TeV via neutron emission, performed using the zero degree calorimeters (ZDCs) of the ALICE experiment [7] at the Large Hadron Collider (LHC). The ZDCs are ideally suited to tag EMD interactions, since the resulting neutrons from the GDR decay are emitted very close to beam rapidity and are the most abundant particles produced in these processes. The data were collected using the neutron ZDCs (ZNA and ZNC), located 114 m away from the interaction point (IP) at the so-called A and C sides of the ALICE detector. Each neutron ZDC (ZN) is placed at zero degrees with respect to the LHC beam axis and is used to detect neutral particles at pseudorapidities $|\eta| > 8.7$. For the present analysis, two small forward electromagnetic calorimeters (ZEM1 and ZEM2), placed on the A side at 7.35 m from the IP ($4.8 \leq \eta \leq 5.7$), are also used to tag hadronic interactions.

The experimental results are presented and compared to theoretical predictions of the Relativistic Electromagnetic Dissociation (RELDIS) model [5], which is designed to describe electromagnetic interactions between ultrarelativistic nuclei including single and double virtual photon absorption, excitation of giant resonances, intranuclear cascades of produced hadrons, and statistical decay of excited residual nuclei. Above the GDR region, photon-induced reactions become more complicated leading to multiple (>3) emission of neutrons [8]. RELDIS accurately reproduces this experimental observation and also predicts further increase of the mean number of neutrons and of the width of their multiplicity distribution as photon energy increases [9]. Calculations based on this model provide a good description of neutron emission in electromagnetic dissociation of Pb ions at the CERN SPS [10] and of Au ions at the Relativistic Heavy Ion Collider (RHIC) [11].

During the $\sqrt{s_{NN}} = 2.76$ TeV Pb-Pb data taking in 2010, an EMD run was performed. In this dedicated run, only the ZDCs and ZEM were read out. The trigger was set to tag neutrons emitted in EMD as well as hadronic interactions (see Fig. 1), requiring a minimum energy deposit in at least one of the two ZNs (~3×10^6 events were collected). The energy thresholds were ~450 GeV for ZNA and ~500 GeV for ZNC and were placed approximately 3 standard deviations below the energy deposition of a 1.38 TeV neutron. The depletion of events in the region

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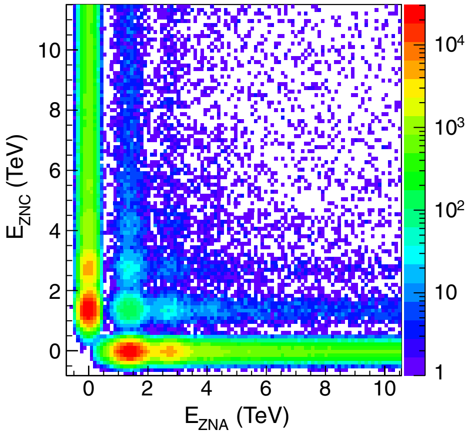

FIG. 1 (color online). Energy deposition in ZNC versus ZNA for single EMD plus hadronic events. The $1n$ signal is at 1.38 TeV. The events where at least $1n$ is detected by both ZNs are associated with mutual EMD and hadronic processes.

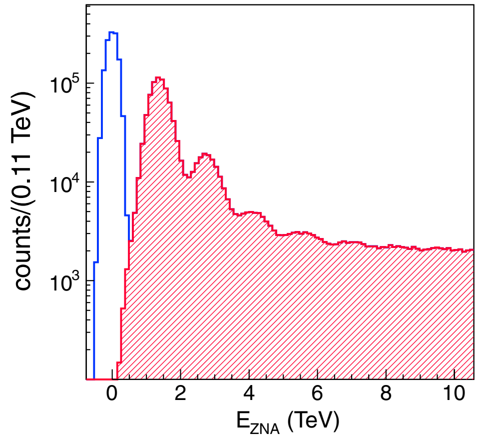

FIG. 2 (color online). ZNA energy spectrum requiring signal over threshold in ZNA or ZNC (unfilled area) superimposed to ZNA energy spectrum requiring signal in ZNA (shaded area). The first peak centered at $E = 0$ corresponds to pedestal events, where no signal from neutron emission is detected by the ZNA.

where the ZNA and ZNC energy deposition is close to 0 TeV is related to the (ZNA or ZNC) trigger onset.

Following a common convention, we define as single EMD a process where at least one neutron ($1n$) is emitted by a given Pb nucleus disregarding the fate of the other nucleus. Mutual EMD events, where at least $1n$ is emitted by both Pb nuclei, and hadronic events were selected offline requiring an energy deposit above the energy threshold in both ZNs.

In the 2010 Pb-Pb run, ZNs were used as the ALICE luminometer, providing different logical combinations of signals (ZDC triggers). In particular during a beam separation van der Meer (vdM) scan [12], a cross section $\sigma^{\rm vdM}_{\rm ZNA\ or\ ZNC} = 371.4 \pm 0.6\,({\rm stat})^{+24}_{-19}\,({\rm syst})$ b was measured for the (ZNA or ZNC) trigger, tagging single EMD plus hadronic interactions. The systematic error of $-5.2\% + 6.4\%$ can be decomposed as follows: 4.3% uncertainty coming from the vdM scan analysis [13], dominated by the calibration of the distance scale during the scan; $-3\% + 4.7\%$ uncertainty coming from the measurement of the beam intensity, dominated by the beam current transformers scale [14] and by the noncolliding (ghost) charge fraction in the LHC beams [15,16]. The beam-gas contribution ($\sim 2.5\%$) is subtracted.

The energy spectrum for the ZNA is shown in Fig. 2, for events in which there is a signal in at least one of the two ZNs (unfilled area) or for events in which ZNA is fired (shaded area). The selection of events with signal in ZNA is performed offline using the timing information provided by a TDC (time to digital converter). This provides a sharper cut with respect to a selection based on energy deposit. In the first case, a pedestal peak centered at $E = 0$ is visible, which corresponds to events where no signal is detected by the ZNA and the trigger is fired by the ZNC. As can be inferred in Fig. 2, the TDC selection rejects only events in the pedestal. The width of the pedestal peak is related to the noise of electronic modules. In the energy spectrum, a pronounced $1n$ peak at 1.38 TeV is present, but also $2n$, $3n$, $4n$ ... peaks are clearly identified. The requirement of a signal in the TDC for the ZNA and the ZNC, respectively, allows us to calculate two different estimates of the number of events from single EMD plus hadronic processes. The average of the two results is then calculated (the difference between the response of the ZNA and the ZNC is about 0.1%). The contamination from beam-residual gas interactions, estimated via the observed rates with circulating beams, before they are brought into collisions, is of the order of 2.5% and is corrected.

A second event selection requires a signal in one of the ZNs, but not in the other one. In this way, hadronic events, which mostly lead to disintegration of both colliding nuclei, are rejected. In this case, the mutual EMD events are also removed from the spectrum and therefore the selected process is the single EMD minus the mutual EMD. The energy spectrum is shown in Fig. 3 together with the fit obtained by summing four Gaussians. The curve for the $1n$ peak has three free parameters, while the following Gaussians describing the ith peak have a constraint both on the mean value μ_{in} ($\mu_{in} = i \times \mu_{1n}$, where μ_{in} is the mean value for the ith neutron peak) and on the width σ_{in} ($\sigma_{in} = \sqrt{i \times (\sigma^2_{1n} - \sigma^2_{\rm ped}) + \sigma^2_{\rm ped}}$, where σ_{in} is the width of the ith neutron peak and $\sigma_{\rm ped}$ is the width of the pedestal peak). The relative energy resolution σ_{1n}/μ_{1n} of the $1n$ peak at 1.38 TeV is 21% for the ZNA and 20% for the ZNC, in agreement with expectations from beam tests at the CERN SPS [17] extrapolated to LHC energies using Monte Carlo simulation, which takes into account the different operating conditions. Similarly to the previous analysis we made the average of the ZNA and the ZNC cross sections, which difference is about 0.2%.

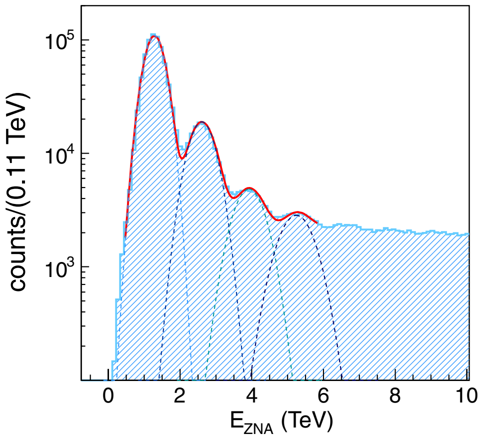

FIG. 3 (color online). ZNA energy spectrum requiring signal over threshold in ZNA but not in ZNC, rejecting thus neutron emission on the opposite side. The dashed lines represent the single fits of the different peaks ($1n, 2n, \ldots$), while the continuous line is the sum of all the contributions.

The cross sections, listed in Table I (first two rows), are calculated using the (ZNA or ZNC) cross section measured during the vdM scan: $\sigma_{\rm proc} = \sigma^{\rm vdM}_{\rm ZNA\ or\ ZNC} \times N_{\rm proc}/N_{\rm ZNA\ or\ ZNC}$, where $N_{\rm proc}$ is the number of events in the sample of the selected process and $N_{\rm ZNA\ or\ ZNC}$ is the number of events collected with the same trigger as used to determine $\sigma^{\rm vdM}_{\rm ZNA\ or\ ZNC}$. The calculated values are corrected for the ZN detection probability [98.7% ± 0.04%(stat) ± 0.1%(syst)], estimated from a Monte Carlo simulation using RELDIS as event generator. The systematic errors, dominated by the uncertainties of the cross sections measured during the vdM scan, take also into account the difference between the response of the ZNA and the ZNC (0.1–0.2%) and the uncertainty due to the estimate of beam-gas background (∼ 1%). The centering of ZN calorimeters on the neutron spot was assured by the measurement of the centroid position, thanks to their transverse segmentation in four towers.

The predictions of the RELDIS model for $\sqrt{s_{\rm NN}} =$ 2.76 TeV Pb-Pb EMD interactions are also shown in Table I. The agreement between data and model predictions is remarkable. In calculations of the EMD cross sections, various approximations of the total photoabsorption cross sections on lead are used, leading to 5% uncertainties in the predicted values [5]. These errors include the difference between RELDIS and other theoretical predictions [18].

TABLE I. Cross sections (barn) for $\sqrt{s_{\rm NN}} = 2.76$ TeV Pb-Pb interactions (systematic errors are dominated by the vdM cross section errors). Theoretical uncertainties are systematic and related to uncertainties in the total photoabsorption cross sections on Pb.

Physical process	Data	RELDIS
Single EMD + hadronic	$194.8 \pm 0.3{\rm stat}^{+13.6}_{-11.5}{\rm syst}$	192.9 ± 9.2
Single EMD − mutual EMD	$181.3 \pm 0.3{\rm stat}^{+12.8}_{-10.9}{\rm syst}$	179.7 ± 9.2
Mutual EMD	$5.7 \pm 0.1{\rm stat} \pm 0.4{\rm syst}$	5.5 ± 0.6
Hadronic	$7.7 \pm 0.1{\rm stat}^{+0.6}_{-0.5}{\rm syst}$	7.7 ± 0.4
Single EMD	$187.4 \pm 0.2{\rm stat}^{+13.2}_{-11.2}{\rm syst}$	185.2 ± 9.2

A third event selection is performed to select mutual EMD and hadronic events requiring a minimum energy deposition in both ZNs. This selection rejects all beam-gas contributions. To disentangle the mutual EMD and the hadronic processes, the ZEMs are used to select events with no signal in any ZEM or a signal in at least one of the two ZEMs, respectively. The energy threshold for each ZEM is about 10 GeV. Figure 4 shows the ZNA energy spectrum for the mutual EMD (continuous line) and hadronic (dashed line) event selection. The cross sections for the mutual EMD and hadronic processes are calculated, as in the previous analysis, using the vdM (ZNA or ZNC) cross section. The ZEM trigger efficiencies for the mutual EMD event selection, i.e., the fraction of mutual EMD events with no signal in any ZEM, is 96.0% ± 0.1%(stat) ± 0.6%(syst), evaluated from simulation using RELDIS as event generator. The ZEM trigger efficiencies for the hadronic event selection, i.e., the fraction of hadronic events with a signal in at least one of the two ZEMs, is 92.4% ± 0.3%(stat) ± 1.0%(syst), estimated using HIJING [19] as event generator, combined with a simple fragmentation model [20]. Since the two event selections are mutually exclusive, the contamination of mutual EMD events in the hadronic sample and of hadronic events in the mutual EMD sample are ∼4% and ∼7.6%, respectively.

The raw cross sections ($\sigma_{m{\rm EMD,raw}}$, $\sigma_{\rm hadr,raw}$) and the ZEM trigger efficiencies ($\epsilon_{m{\rm EMD}}$, $\epsilon_{\rm hadr}$) for the two processes are inserted in a system of equations in two variables, where the unknowns are the true mutual EMD and the true hadronic cross sections ($\sigma_{m{\rm EMD,true}}$, $\sigma_{\rm hadr,true}$), respectively,

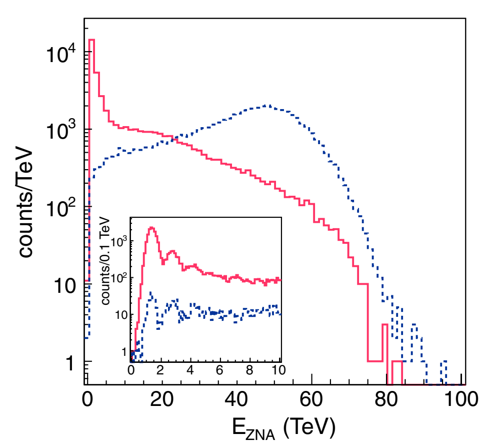

FIG. 4 (color online). ZNA energy spectrum for mutual EMD (no signal in any ZEM, continuous line) and hadronic (a signal in at least one of the two ZEMs, dashed line) event selection. The inset shows an expanded view of the low-energy region.

TABLE II. Neutron emission fractions for single EMD minus mutual EMD process in $\sqrt{s_{NN}} = 2.76$ TeV Pb-Pb interactions. Theoretical uncertainties are systematic and related to the divergence of predictions of various photonuclear reaction models.

Ratio	Data (%)	RELDIS (%)
$1n/N_{tot}$	51.5 ± 0.4stat ± 0.2syst	54.2 ± 2.4
$2n/N_{tot}$	11.6 ± 0.3stat ± 0.5syst	12.7 ± 0.8
$3n/N_{tot}$	3.6 ± 0.2stat ± 0.2syst	5.4 ± 0.7
$2n/1n$	22.5 ± 0.5stat ± 0.9syst	23.5 ± 2.5

$$\sigma_{m\mathrm{EMD,raw}} = \epsilon_{m\mathrm{EMD}} \cdot \sigma_{m\mathrm{EMD,true}} + (1 - \epsilon_{\mathrm{hadr}}) \cdot \sigma_{\mathrm{hadr,true}},$$
$$\sigma_{\mathrm{hadr,raw}} = (1 - \epsilon_{m\mathrm{EMD}}) \cdot \sigma_{m\mathrm{EMD,true}} + \epsilon_{\mathrm{hadr}} \cdot \sigma_{\mathrm{hadr,true}}. \quad (1)$$

The extracted values are corrected for the estimated ZN detection probability for mutual EMD [95.7% $\pm$ 0.07%(stat) $\pm$ 0.5%(syst)] and for hadronic [97.0% $\pm$ 0.2%(stat) $\pm$ 3%(syst)] events. The mutual EMD cross section is also corrected for background from accidental coincidences between uncorrelated single EMD interactions ($\sim$ 10%). The final cross section results are summarized and compared to the RELDIS predictions in Table I (third and fourth rows).

The single EMD cross section listed in Table I (last row) is estimated from previous measurements, making an average of the (single EMD + hadronic) − hadronic and the (single EMD − mutual EMD) + mutual EMD cross sections.

For the single EMD − mutual EMD event selection, the measured fractions of $1n$, $2n$, and $3n$ events with respect to the total number of events is estimated (Table II). The table contains also the relevant expectations for the ratios based on the calculations with the RELDIS model. The $1n$ and $2n$ emission channels give the main contribution (63%), confirming that EMD processes proceed predominantly via GDR excitation and subsequent decay by neutron emission. According to RELDIS, $3n$ emission is mostly induced by energetic ($>$ 40 MeV) equivalent photons and frequently accompanied by emission of protons and pions. The measured $1n$ and $2n$ yields are much closer to RELDIS predictions compared to the $3n$ yields. This can be explained by the fact that RELDIS was already tuned by comparison with $1n$ and $2n$ data on photoabsorption on lead [5] and on EMD of 30 A GeV lead nuclei [10]. Unfortunately, the data on neutron emission induced by photons above 140 MeV are absent, while according to RELDIS almost half of $3n$ events is due to such energetic photons. In EMD calculations, the native photonuclear reaction model of RELDIS can be replaced by the GNASH code [21], thus providing slightly different results for $1n$ and $2n$ yields. On the basis of this difference, the theoretical uncertainties listed in Table II are estimated.

Our $2n$ to $1n$ ratio of $(22.5 \pm 0.5 \pm 0.9)$% in single EMD can be compared to the value of (19.7 ± 2.9)% reported for Pb-Pb collisions at 30 A GeV at the CERN SPS [10]. As predicted by RELDIS, the observed weak increase (around 1 standard deviation) of the $2n$ to $1n$ ratio with collision energy is due to additional $2n$ events produced by more energetic equivalent photons at the LHC.

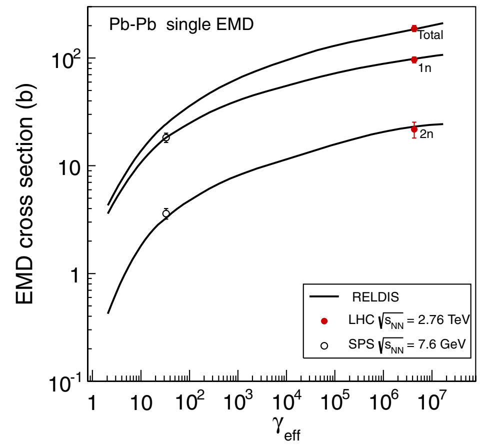

FIG. 5 (color online). Total single EMD cross sections and partial EMD cross sections for emission of one and two neutrons as a function of the effective Lorentz factor γ_{eff}. The closed symbols are our data, while the open symbols represent the results obtained at CERN SPS [10] at 30 GeV. The RELDIS predictions [10] for total, $1n$, and $2n$ EMD cross sections are shown as solid lines.

Finally, Fig. 5 presents total and partial EMD cross sections for emission of one and two neutrons measured by ALICE compared to CERN SPS data [10]. The results of the RELDIS model are also shown for a wide range of the projectile effective Lorentz-factor γ_{eff} calculated in the rest frame of the collision partner. As seen, both data sets are successfully described by the model despite a six orders-of-magnitude span of γ_{eff}. A direct comparison to RHIC results is not straightforward since the structure of the involved nuclei is different. Since ^{208}Pb is a double magic nucleus, while ^{197}Au is not, the GDR position, its width as well as the neutron emission thresholds differ in such nuclei.

In summary, a first measurement of electromagnetic dissociation in $\sqrt{s_{NN}} = 2.76$ TeV Pb-Pb collisions was performed at the LHC by detection of the emitted neutrons with the ALICE ZDCs. The measurement tests the theoretical predictions used for estimations of beam losses. The RELDIS model predictions are in a very good agreement with our experimental results. The measurements reported here establish experimentally the EMD cross section scale for the first time at LHC energy. We finally note that the ALICE ZDC detectors, calibrated through these results, provide the possibility of a direct absolute measurement of the LHC luminosity in Pb-Pb collisions.

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