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Single and double photonuclear excitations in Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV at the CERN Large Hadron Collider

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Cross sections are calculated for single and double photon exchange in ultraperipheral Pb + Pb collisions at the CERN Large Hadron Collider. The particle production is simulated with the DPMJET event generator. Large cross sections are found for particle production around midrapidity, making these processes an important background to hadronic nuclear interactions at both the trigger and analysis levels.

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The strong electromagnetic fields present in high-energy nuclear collisions with impact parameters larger than the sum of the nuclear radii lead to large cross sections for a variety of photonuclear processes. In these ultraperipheral collisions, there are no geometrical overlaps between the colliding nuclei, so purely hadronic interactions are suppressed. Particle production in ultraperipheral collisions has been studied in Au + Au collisions at the BNL Relativistic Heavy-Ion Collider (RHIC) and in heavy-ion interactions at lower energies. See Ref. [1] for a review. These studies have so far been focused on the exclusive production of a single (vector) meson, e.g., Au + Au → Au + Au + V with $V = \rho^0$ or J/Ψ, or on two-photon production of dilepton pairs. The nuclei have remained intact or have only been excited to low energies by the exchange of an additional soft photon.

In this Rapid Communication, we consider particle production in a general photonuclear interaction, $\gamma + A \to X$ in ultraperipheral collisions between two lead nuclei at the CERN Large Hadron Collider (LHC). We do the calculations for the collision energy $\sqrt{s_{NN}} = 2.76$ TeV which will be available during the first two heavy-ion runs in 2010 and 2011/12. As will be discussed further below, the relevant photon energies for particle production around midrapidity are between ∼10 GeV and ∼100 TeV in the rest frame of the target nucleus. We consider the cases when one or two photons are exchanged. In the former case, the photon-emitting nucleus remains intact, $A + A \to A + X$, while in the latter case both nuclei disintegrate. The particle production in the photonuclear interactions is modeled using the DPMJET Monte Carlo event generator version 3.0 [2,3].

We begin by discussing the photon flux associated with relativistic heavy ions and derive the relevant spectrum for single and double photon exchange. We then discuss particle production in these collisions and how the produced particles are distributed in phase space. We conclude by briefly discussing the experimental consequences of these processes in a typical high-energy collider experiment.

The electromagnetic field of a relativistic particle can be treated as an equivalent flux of photons. This is the Weizsäcker-Williams method. For collisions between relativistic nuclei, the photon spectrum should be calculated in impact parameter space [4,5]. In this way, interactions with nuclear overlap, where the strong interaction dominates, can easily be excluded. The difference between this approach and using a nuclear form factor for calculating the photon spectrum will be discussed below.

The photon spectrum, dn/dk, of one ion in an ultraperipheral collision is given by an integral over the impact parameter b,

$$\frac{dn}{dk} = 2\pi \int_0^\infty \frac{d^3n}{dk\,db^2}[1 - P_{\mathrm{had}}(b)]b\,db. \tag{1}$$

The cutoff at small impact parameters ∼$2R$ is implemented using a smooth function for the probability of not having any hadronic interaction $[1 - P_{\mathrm{had}}(b)]$; $P_{\mathrm{had}}(b)$ is calculated from a Glauber model. Since the photonuclear interaction probabilities are highest in grazing collisions with impact parameters $b \approx 2R$, it is important to take the hadronic interaction probability into account properly and not rely on a simple cutoff at $b = 2R$ (see Fig. 1 below). The doubly differential photon spectrum $d^3n/dk\,db^2$ is

$$\frac{d^3n}{dk\,db^2} = \frac{Z^2\alpha}{\pi^2}\frac{1}{kb^2}x^2K_1^2(x), \tag{2}$$

where $x = bk/\gamma$ and $\gamma \gg 1$ is the Lorentz factor.

The cross section for a photonuclear interaction with photons from a single beam is then given by

$$\sigma_{A+A\to A+X} = \int_{k_{\min}}^\infty \frac{dn}{dk}\sigma_{\gamma A}(k)\,dk. \tag{3}$$

The integral is cut off by the rapid decrease of the photon spectrum for $k > \gamma/R \approx 120$ TeV in the rest frame of the target nucleus.

By inserting the expression for dn/dk from Eq. (1) into Eq. (3) and changing the order of integration, the first-order photonuclear interaction probability as a function of impact parameter can be obtained through differentiation:

$$P_1(b) = \frac{d\sigma}{db^2} = \int_{k_{\min}}^\infty \frac{d^3n}{dk\,db^2}\sigma_{\gamma A}(k)\,dk. \tag{4}$$

The photonuclear interaction probability as function of impact parameter is shown in Fig. 1 for three different values of $k_{\min} = 6$ GeV, 1000 GeV, and 10 TeV. The minimum value, 6 GeV, is chosen as the lowest photon energy that can be

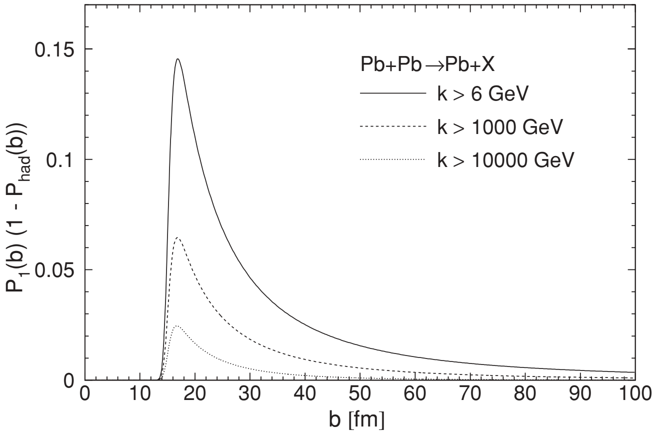

FIG. 1. Probability for having a photonuclear interaction and no hadronic interaction as a function of impact parameter for three different minimum photon energies, $k_{\min}$.

handled by DPMJET. The effect of this minimum on particle production in different rapidity intervals will be discussed further below. The photonuclear cross section, $\sigma_{\gamma A}(k)$, is the cross section for particle production calculated by DPMJET; it depends weakly on the photon energy k, and increases monotonically from 8.1 to 12.9 mb over the relevant energy range (6 GeV–100 TeV).

The total photon-proton cross section has not been measured above center-of-mass energies of 200 GeV, and there is thus some uncertainty in the energy dependence at the highest energies [11]. The energy dependence of the photonuclear cross section should, however, be weaker because of shadowing, which implies that only the edges of the nuclei are affected by the increase. The contribution to the total cross section from photons with these high energies ($k > 21$ TeV) is furthermore rather low, so this uncertainty will not significantly affect the results presented here.

The interaction probability has a maximum of ≈15% for $k_{\min} = 6$ GeV in grazing collisions with impact parameter ≈16 fm. For $k_{\min} = 1000$ GeV and 10 TeV, the corresponding maximum probabilities are 6% and 2%, respectively. These high probabilities make exchange of multiple photons in the same event likely. For cases where the collision time b/γ is much smaller than the excitation time, $1/k$, the sudden approximation applies, and the probability for multiple photon exchange factorizes [6]. This method has been used previously to calculate the total cross sections for correlated forward-backward Coulomb dissociation [7]. The cross section for exchanging one photon from each nucleus is thus given by

$$\sigma_{AA} = 2\pi \int_0^\infty [P_1(b)]^2[1 - P_{\text{had}}(b)]b\,db. \tag{5}$$

The photon energy spectrum for double excitation is obtained by differentiating Eq. (5) with respect to the photon energies k_1 and k_2. The result can be written

$$\frac{d\sigma}{dk_1\,dk_2} = 2\pi \int_0^\infty \frac{d^3n}{dk_1\,db^2}\sigma(k_1)\frac{d^3n}{dk_2\,db^2}\sigma(k_2) \times [1 - P_{\text{had}}(b)]b\,db. \tag{6}$$

It is worth noting that there is a positive correlation between the two photon energies. The photon spectrum from a single nucleus under the requirement that the other nucleus emits a photon is obtained by integrating over either k_1 or k_2. The result is

$$\frac{d\sigma}{dk_1} = 2\pi \int_0^\infty \frac{d^3n}{dk_1\,db^2}\sigma(k_1)P_1(b)[1 - P_{\text{had}}(b)]b\,db. \tag{7}$$

The spectrum is thus weighted toward a smaller impact parameter by the photonuclear interaction probability $P_1(b)$, resulting in a harder spectrum. This is in agreement with what was found for photonuclear vector meson production in coincidence with Coulomb breakup [8].

Although the interaction probabilities for these photon energies are fairly high, they are sufficiently smaller than unity for the first-order probabilities to be used. Unitarity restoration [6] has been estimated to reduce the cross sections with at most a few percent.

A high-energy photon may interact with a nucleon or nucleus in two different ways: it can appear as a bare photon, which interacts with a parton in the target, or it can first fluctuate to a $q\bar{q}$ pair, which then interacts with the target via the strong interaction, see e.g., Refs. [9,10]. The importance of the hadronic component of the photon at high-energy electron-proton colliders has been pointed out earlier [9]. Since the quantum numbers of the photon are 1^{--}, it tends to fluctuate to a virtual vector meson (vector meson dominance). The bulk of the photonuclear cross section and the soft particle production can be understood from resolved vector meson interactions.

The DPMJET [2,3] Monte Carlo event generator is based on the two-component dual parton model. The resolved part of the photon-hadron interaction is handled by the dual parton model through its implementation in PHOJET. The scaling from photon-hadron to photon-nucleus interactions, including shadowing, is treated within the framework of the Gribov-Glauber approximation. The high-p_T partonic processes are calculated from lowest order perturbative QCD. The model has been tested against data from fixed target π-nucleus, p + nucleus, and μ + nucleus experiments. It has been shown to reproduce the bulk particle production well [3]. It can handle low or intermediate photon virtualities, which is fine in this case, since the photons from the Weizsäcker-Williams fields have very low virtualities $Q^2 \leqslant (1/R)^2 \approx 10^{-3}$ GeV^2. The fragmentation of the target nucleus is not considered in the current version of DPMJET, but knockout protons from the target remnant are included.

Samples of events have been generated with DPMJET with the photon spectrum described in the previous section and with different minimum photon energies. Six samples have been generated with 500 000 events per sample. Samples with single and double excitation have been generated with values of $k_{\min} = 6$, 1000, and 10 000 GeV. The cross sections for these samples are listed in Table I. The table also includes the corresponding cross sections when it is required that

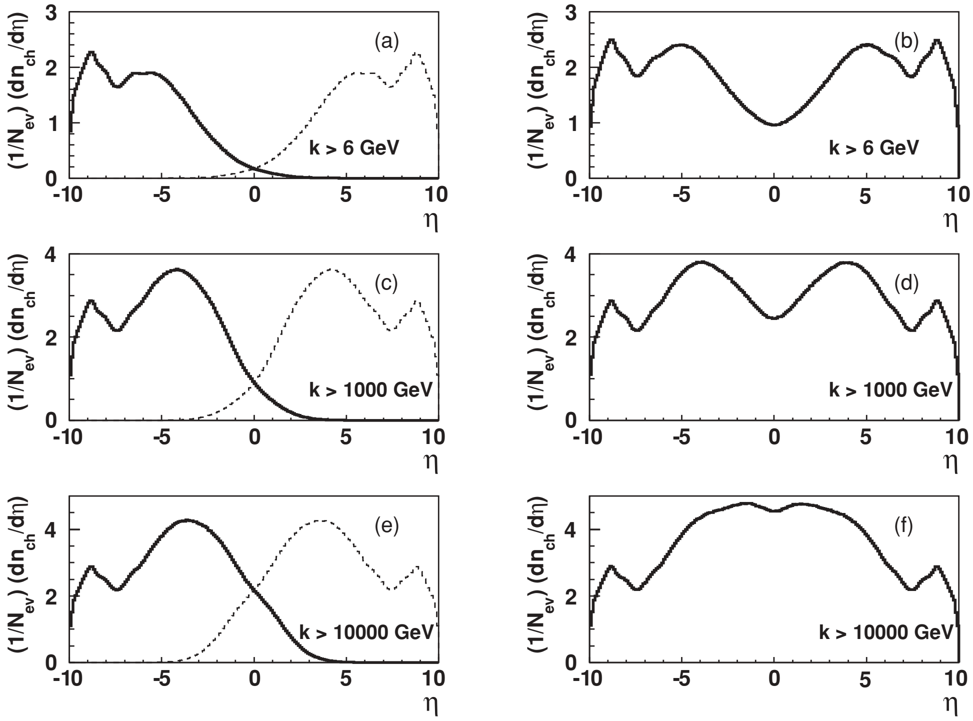

FIG. 2. Pseudorapidity distributions of charged particles for different minimum photon energies for single (left) and double (right) excitations with different cutoff energies, $k_{\min}$. For single excitations, the solid histograms are for photoproduction off the nucleus with negative rapidity and the dashed histogram corresponds to production off the nucleus with positive rapidity. The peaks around $\eta = \pm 9$ are from knockout protons from the target nucleus.

there should be at least one charged particle at central rapidities.

The normalized charged particle pseudorapidity [$\eta = -\ln(\tan\frac{\theta}{2})$] density distributions for the samples are shown in Figs. 2(a)–2(f). As expected, the particle production becomes more centered around midrapidity with increasing photon energy. The corresponding multiplicity distributions of charged particles with $|\eta| < 1$ are shown in Figs. 3(a)–3(f).

The cross sections in Table I are huge. The total photoproduction cross section for $k > 6$ GeV is about three times

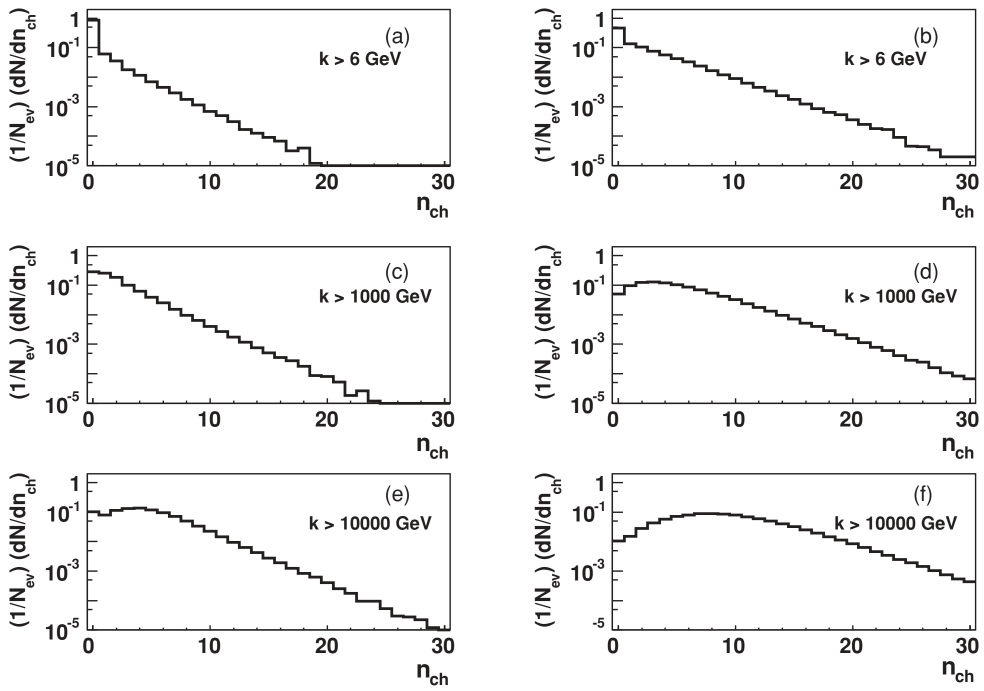

FIG. 3. Multiplicity distributions of charged particles at midrapidity $|\eta| < 1$ for single (left) and double (right) excitations with different cutoff energies, $k_{\min}$.

TABLE I. Cross sections for particle production for single and double photonuclear excitations with different minimum photon energies, k_{min}. The total cross sections and the cross sections for having at least one charged particle within $|\eta| < 1$ are shown. The cross sections for single excitations take into account that both nuclei can act as photon emitter and target.

k_{min}	Single, σ (b)		Double, σ (mb)	
(GeV)	All	$n_{\text{ch}}(\|\eta\| < 1) \geqslant 1$	All	$n_{\text{ch}}(\|\eta\| < 1) \geqslant 1$
6	24.2	4.5	240	130
1000	4.9	3.5	42	40
10 000	0.90	0.81	4.8	4.8

larger than the total hadronic cross section. If one requires at least one photoproduced charged particle within $|\eta| < 1$, the cross section is about 4 b or roughly 50% of the total hadronic cross section. As can be inferred from Fig. 3, the probability for having larger multiplicities around midrapidity is also very high. It is essential, especially for the higher values of k_{min}, to calculate the photon spectrum in the impact parameter space. If a form factor (a convolution of a hard sphere and Yukawa form factor [8]) is used, the cross section for single excitation with $k_{\text{min}} = 6$ GeV has been found to be 30% higher than in Table I. For $k_{\text{min}} = 1000$ and 10 000 GeV, the differences are 73% and 185%, respectively. Using a nuclear form factor does not remove the contribution from events where the nuclei overlap.

The transverse momenta of the photoproduced particles are typical for soft hadron-nucleus interactions. The p_T distribution at midrapidity for single production with $k_{\text{min}} = 6$ GeV is shown in Fig. 4(a). The distribution is essentially the same for all samples studied with a mean transverse momentum of $\langle p_T \rangle \approx 450$ MeV$/c$.

The large cross sections and the characteristics of these interactions should make them an important background to hadronic nuclear interactions at colliders. Single excitations, which have the largest cross sections, are characterized by a strong asymmetry around mid-rapidity event-by-event. They can thus to some extent be rejected by requiring the presence of particles on either side of midrapidity. The cross sections for double excitations are lower, but these events have particles produced over a wider range of rapidities. They may therefore be harder to separate from hadronic interactions with low or intermediate multiplicities.

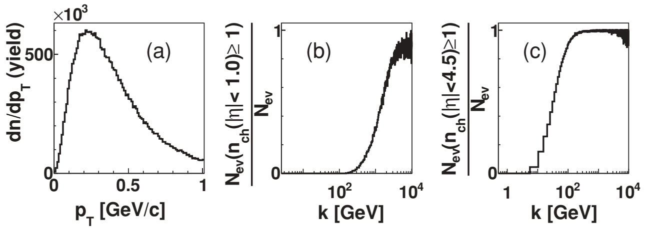

FIG. 4. (a) Transverse momentum distribution of charged particles within $|\eta| < 1$. (b) Fraction of events with at least one charged particle within $|\eta| < 1$ as function of photon energy. (c) Same as (b) but for $|\eta| < 4.5$.

The photon spectrum, of course, extends to, in principle, arbitrarily low values of k. The lowest $k_{\text{min}} = 6$ GeV used here is therefore in that sense arbitrary. However, for particle production around midrapidity, photons with low energy do not contribute. This is illustrated in Figs. 4(b) and 4(c). Figure 4(b) shows the ratio of the number of events with at least one charged particle within $|\eta| < 1$ to all events as a function of photon energy. The distribution goes to zero around $k \approx 150$ GeV, and photons with energy lower than this do thus not contribute to the particle production within the two most central units of pseudorapidity. Figure 4(c) shows the same distribution for events with at least one charged particle within $|\eta| < 4.5$. The ratio goes to zero above the lowest $k_{\text{min}} = 6$ GeV used here. The photon energy range considered should thus give a complete description of photoproduction within the nine most central units of pseudorapidity, $|\eta| < 4.5$.

Unlike exclusive production of single mesons or dilepton pairs, inclusive photoproduction in ultraperipheral collisions has so far attracted rather limited interest. Some early studies were done for RHIC [12], mainly to find the background rates for exclusive production. The cross sections are about an order of magnitude lower at RHIC energies ($\sqrt{s_{NN}} = 200$ GeV) than at the LHC. Inclusive photoproduction of mesons in high-energy heavy-ion interactions were also studied in Ref. [13]. The results are not directly comparable to the present work, because of a lower minimum photon energy, k_{min}, and because only multiple photons hitting the *same* nucleus were considered.

We have calculated the photon energy spectrum for single and double photonuclear excitations in Pb + Pb collisions at the LHC. Events have been generated with the DPMJET Monte Carlo according to these spectra. Large cross sections are found also for particle production around midrapidity.

The large cross sections and the nonzero probability for having charged particles produced with intermediate or high p_T around midrapidity make these events an important background to peripheral and semicentral Pb + Pb collisions at the LHC. They have to be taken into account in order to correctly determine what fraction of the total hadronic cross section a given event selection corresponds to.

If the photonuclear events can be clearly separated from the hadronic events, e.g., using the rapidity gap between the photon-emitting nucleus and the produced particles, much interesting physics could be extracted from them. The cross section to produce a $c\bar{c}$ pair through γ + gluon fusion is, for example, nearly 1 b at the full LHC energy [14]. If these events can be measured, they would provide valuable information on the nuclear parton distribution functions.

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