Characterization of hadron production in $\gamma - A$ photonuclear interactions of ultra-peripheral collisions

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Abstract
A methodology for the simulation of ultra-peripheral collisions, specifically ultra-relativistic heavy ion ^{197}Au-^{197}Au and p-^{208}Pb collisions, is developed. First, the fluxes of virtual photons as a function of the photon energy and the impact parameter are obtained using the Method of Weizsäcker-Williams. Then, the processes induced by photons in photon-hadron collisions γ+Au, γ+p and γ+Pb are simulated, neglecting the photon-photon contribution. The model is implemented in the code CRISP (Collaboration Rio-Sao Paulo), specifically designed for simulations of the nuclear environment. Cross-section, differential cross-section, multiplicity, invariant mass spectrum, angular distribution and p_T distribution in ^{197}Au-^{197}Au and p-^{208}Pb collisions are obtained, and a comparison with experimental data is accomplished in order to validate the model.

Key words: *collisions; nuclei; cross sections; photons; experimental data.*

Caracterización de la producción de hadrones en interacciones fotonucleares $\gamma - A$ de colisiones ultraperiféricas

Resumen
Una metodología para la simulación de colisiones ultraperiféricas, específicamente colisiones ultrarelativistas de iones pesados ^{197}Au-^{197}Au y p-^{208}Pb es desarrollada. Primero, los flujos de fotones virtuales como función de la energía del fotón y el parámetro de impacto son obtenidos, usando el Método de Weizsäcker-Williams. Luego, los procesos inducidos por fotones en colisiones fotón-hadrón γ+Au, γ+p y γ+Pb son simulados, despreciando la contribución fotón-fotón. El modelo es implementado en el código CRISP (Colaboración Rio-Sao Paulo), específicamente diseñado para simulaciones del ambiente nuclear. La sección eficaz, sección eficaz diferencial, multiplicidad, espectro de masa invariante y distribución de p_T son obtenidas, y se realiza una comparación con resultados experimentales, con el objetivo de validar el modelo.

Palabras clave: *colisiones; núcleos; secciones eficaces; fotones; datos experimentales*

Introduction

The electromagnetic excitation of the nucleus $(\gamma + {}^{A}_{Z}X \rightarrow b + {}^{A}_{Z}X)$, known as photonuclear interaction, is a powerful tool for the study of the dynamics and nuclear structure. Recently, the particle accelerators have caught up with electromagnetic fields strong enough to study processes that happen at energy of the incident photons never previously reached [1]. The theoretical foundation that laid the groundwork for the study of the photoproduction of particles in collisions between ions was given in 1924 by Enrico Fermi, when he published in the german journal “Zeischrift Für Physic” the article “One Theory of Collisions Between Atoms and Elastically Charged Particles”. In this work he explains a procedure known as “Method of Virtual Photons”, where he states that the electromagnetic field of a charged particle is equivalent to a flux of photons with an energetic continuous spectrum. In 1935, Weizsäcker and Williams, in an independent manner, extended the applicability of the equivalence stated by Fermi, for the case of charged relativistic particles, which is why this method is often known as “Method of Weizäcker-Williams”. In 1938, V.F. Weisskopf exposes his ideas about the theme in Physical Review [2]: “Charged particles are able to excite nuclei without penetrating into the nucleus by means of the action of their electric field upon the nucleus when they pass nearby”.

The collisions between hadrons can be split into three categories taking into account the parameter of impact b. In the first category the collision occurs with a geometric overlap of hadrons and receives the name of central collision, where the impact parameter is minor than the sum of the radios of both particles $b<R_1+R_2$ (R_1 and R_2 are the radios of particle 1 and 2 respectively). When the parameter of impact is $b\approx R_1+R_2$, collisions are referred as peripheral, and if the sum of both radios is $b>R_1+R_2$, ultra-peripheral. In the last case, because there is not overlap between the interacting particles, the strong interaction is inhibited.

In the present work the photonuclear interactions in heavy ions are studied, analyzing their contribution to the production of hadrons in ultra-peripheral symmetric and asymmetric collisions. To accomplish this goal a methodology for the simulation of photonuclear interactions in ultra-peripheral collisions that includes the weigh-in of the spectrum of photons is developed with the code CRISP. The mesonic resonances at energies of the incident photon under 1 GeV are explored. Getting the weigh-ins of the spectrums of Weizsäcker-Williams for the ultra-peripheral collisions symmetric (^{197}Au-^{197}Au, $\sqrt{s_{nn}} = 200\text{ GeV}$) and asymmetric ($^{p\text{-}208}$Pb, $\sqrt{s_{nn}} = 5{,}02\text{ TeV}$) and comparing them with the reported in the literature is other of the tasks accomplished. The influence of the inclusion of the weigh-in of the spectrum in the production of hadrons in ultra-peripheral collisions is also estimated.

Materials methods and results

II. Methodology of Monte Carlo's Simulation for Ultra-peripheral Collisions

Monte Carlo's simulation for ultra-peripheral collisions, symmetric and asymmetric, consists of two steps [3]. First, obtaining the fluxes of virtual photons as a function of the energy of the photon and the impact parameter. The second step consists in simulating γx and γA interactions.

In the process of conception of the simulation it is important to take into account that the code CRISP doesn't have implemented the interaction of a spectrum of photons with a nucleus, but of a monochromatic photon with the target.

The simulations are carried out taking into account the following steps:

–The energetic spectrum of the photons coming from one of the nucleus of ^{197}Au in ^{197}Au- ^{197}Au is split into 2 GeV's 150 energetic steps with 10000 effective cascades.

–The energetic spectrum of the photons coming from the proton in $^{p\text{-}208}$Pb is split into 3 energetic ranges.

–(0-1.615) GeV, with an energetic step of 0,030 GeV and 1000 effective cascades.

–(2-50) GeV, with an energetic step of 1 GeV and 10000 effective cascades.

–(66.5-940.5) GeV, with an energetic step of 19 GeV and 1000 effective cascades.

–The interaction of monochromatic photons in γ-^{197}Au and γ-^{208}Pb with energy value of the top end of the corresponding energy bin is simulated.

–The photoproduction cross-section of particles for each Eγ value is obtained.

–All the contributions are added up to obtain the total cross-section of the photonuclear interaction:

$$\sigma_{xA} \rightarrow_{(xAY)} (y) = \sum_{i=1}^{150} N_{\gamma A}(y, y+\Delta y)_i \sigma_{\gamma x} \rightarrow_{(Yx)} (y+\Delta y)_i + \sum_{i=1}^{150} N_{\gamma x}(y, y+\Delta y)_i \sigma_{\gamma A} \rightarrow_{(YA)} (y+\Delta y)_i \quad (1)$$

III. Simulation of the ultra-peripheral symmetric collision ^{197}Au-^{197}Au at $\sqrt{s_{nn}} = 200\text{ GeV}$

Obtaining of the flux of virtual photons for the ^{197}Au nucleus

The spectrum of virtual photons of the ^{197}Au nucleus was obtained in terms of the rapidity of the J/Ψ meson:

$$y = log\,\frac{2w}{m_{J/\Psi}} \quad (2)$$

The following expression appears in review papers for the photon flux of a fast moving charged particle:

$$N_{\gamma/Z}(w) = w \cdot \frac{\mathrm{d}N_{\gamma/Z}(w)}{\mathrm{d}w} = \frac{2Z^2\alpha_{em}}{\pi} \cdot \int_0^\infty \mathrm{d}q_\perp q_\perp{}^3 [\frac{F_Z\,(q_\perp{}^2+\frac{w^2}{\gamma_L{}^2})}{\left(q_\perp{}^2+\frac{w^2}{\gamma_L{}^2}\right)}]^2 \quad (3)$$

where α_{em} is the fine structure constant, $F_Z(Q^2)$ is the charge form factor, w de energy of the emitted photon and γ_L the Lorentz factor. The spectrum was calculated with the Weizsäcker- Williams classical analytical expression [1]:

$$N_{\gamma/Z}(w) = \frac{2Z^2\alpha_{em}}{\pi} \cdot \left\{\zeta K_0(\zeta)K_1(\zeta) - \frac{\zeta^2}{2}\left[K_0{}^2(\zeta) - K_1{}^2(\zeta)\right]\right\} \quad (4)$$

were $\zeta = \frac{wb_{min}}{\gamma_L}$, K_0 and K_1 are the Modified Bessel functions. The maximum value for the energy of the photons is calculated with γ_{lab} =22 997 in the laboratory frame, obtaining wmax =312 GeV.

IV. Simulation of the ultra-peripheral asymmetric p-^{208}Pb collision at $\sqrt{s_{nn}} = 5{,}02\text{ TeV}$

First, the fluxes of virtual photons from the proton and lead, reported in literature [4], that have a better precision, are compared with the calculus performed in this contribution (4). In the case of the proton, Guzey and Zhalov use the dipole approximation of $F_Z(Q^2)$, and with this:

$$F_p(Q^2) = \frac{1}{[1+\frac{Q^2}{(0.71GeV)^2}]^2} \quad (5)$$

Also, it is used the approximated expression:

$$N_{\gamma/p}(w) = \frac{2\alpha_{em}}{\pi} \cdot \left[1 + \left(1 - \frac{2w}{\sqrt{s_{nn}}}\right)\right] \cdot \left[\log D - \frac{11}{6} + \frac{3}{D} - \frac{3}{2D^2} + \frac{1}{3D^3}\right] \quad (6)$$

where: $$D = 1 + 0.71\text{GeV}^2\left(\frac{\gamma_L{}^2}{w^2}\right) \quad (7)$$

The following figure represents the flux of photons $N\gamma/p$ of the ultra-relativistic proton as a function of the rapidity of the J/ψ meson:

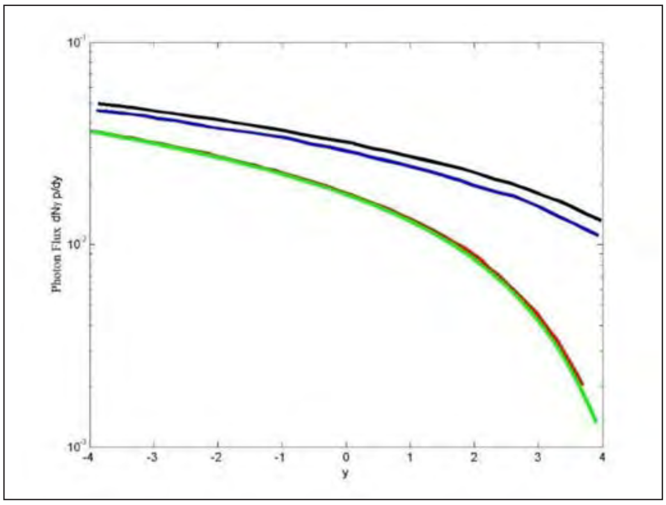

Figure 1. Flux of equivalent photons Nγ/p (ω) in p-[208]Pb collision at $\sqrt{s_{nn}} = 5{,}02\ \mathrm{TeV}$.

In the figure the exact calculation of the equation representing the flux of a relativistic charged particle (3) is given by the blue curve and the approximate result from (6) by the black curve. In order to add more accuracy to the determination of the flux of photons, Guzey and Zhalov took into account the suppression of the strong interaction between the colliding particles. The resulting flux of photons for the proton is calculated in the following way:

$\Gamma_{pA}(\vec{b})$ is the probability of suppressing the nuclear strong interaction for small impact parameters b, and it is calculated as:

$$N_{\gamma/p}(w) = \int_0^{\infty} d^2\vec{b}\, \Gamma_{pA}(\vec{b}) N_{\gamma/p}(w,\vec{b}) \quad (8)$$

$$N_{\gamma/p}(w,\vec{b}) = w \cdot \frac{dN_{\gamma/p}(w,\vec{b})}{dw} = \frac{\alpha_{em}}{\pi^2} \cdot \left[\int_0^{\infty} dq_\perp \frac{q_\perp{}^2 F_p\left(q_\perp{}^2 + \frac{w^2}{\gamma_L{}^2}\right)}{\left(q_\perp{}^2 + \frac{w^2}{\gamma_L{}^2}\right)} J_1(bq_\perp)\right]^2 \quad (9)$$

$$\Gamma_{pA}(\vec{b}) = \exp\left[-\sigma_{nn} \int_{-\infty}^{\infty} dz \rho_A(Z,\vec{b})\right] \quad (10)$$

where σnn is the total nucleon-nucleon cross-section (σnn=90mb at $\sqrt{s_{nn}} = 5{,}02\ \mathrm{TeV}$) and $\rho_A(\vec{r})$ is the nuclear density. The flux of photons Nγ/p, calculated using the equations (8), (9) and (10), is presented in the red line in the figure. The green curve is obtained implementing the expression (4) in the program MATLAB. The program Engauge Digitizer is used to place it next to the three approximations reported in literature. This allow us observing that it agrees with the most precise calculations accomplished by Guzey and Zhalov, which is why their use is valid in the present contribution.

Nγ/Pb is also presented including the approximation (4) for the Pb nucleus, in green color. First, the blue curve correspond to the calculations performed turning down the suppression of the nuclear strong interaction by means of the placement of $\Gamma_{pA}(\vec{b}) = 1$ in the equation (8) and using the upper limit: $b_{min} = R_{Pb}$. Second, the black curve corresponds to the evaluation of Nγ/Pb (3), with the chargeform factor of the lead nucleus. The range of the impact parameter b, considered for the calculation of the integral, is from b_{min}=8 fm to $b_{max}=10^5$ fm. Here it is corroborated the implementation of the expression (4), more simple, for the calculation of the virtual photon's flux for the lead nucleus, the same as in the case of the proton.

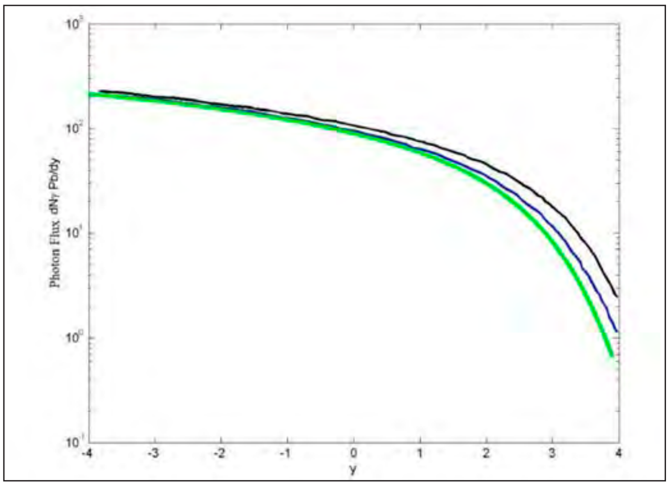

Figure 2. Flux of equivalent photons Nγ/Pb (ω) in p-[208]Pb collision at $\sqrt{s_{nn}} = 5{,}02\ \mathrm{TeV}$.

A. Production of light mesons. Resonances

The cross-section of production of π0 mesons as a function of the incident photon's energy for the reaction: γ+p→p+π0 is studied. A resonance is observed for 340 MeV's energy of the incident photon in the laboratory frame, corresponding to 1232 MeV's energy in the center of momentum frame for γ–p.

The study of the incoherent γ–p mechanism is worthy of notice because it initiates the process of intranuclear cascade. The same resonance obtained in the simulation confirms the importance of the Δ(1232 MeV) resonance in the production of pions, in agreement with the experimental results reported in literature [5].

B. p_T distribution and invariant mass spectrum

The p_T distribution obtained in the simulation is compared hereafter with the reported by CMS experiment for the p-[208]Pb run at $\sqrt{s_{nn}} = 5{,}02\ \mathrm{TeV}$ [6]. The p_T spectrum corresponding to $\langle N_{tracks} \rangle$=8, that's to say, a small value for the multiplicity of particles reported by CMS collaboration is selected, since the ultra-peripheral events are characterized by having a smaller multiplicity and $\langle p_T \rangle$ with regard to central collisions.

It is observed that, the multicollisional dynamics implemented at CRISP, initiated by photonuclear interactions, is capable of reproducing with an acceptable precision the p_T distribution of opposite charged pions.

Another magnitude of concern that allows the identification of particles when an experimental spectrum is analysed is the invariant mass. In a range between 100 MeV/c² and 200 MeV/c² the invariant mass was obtained in the simulation and the π resonance observed.

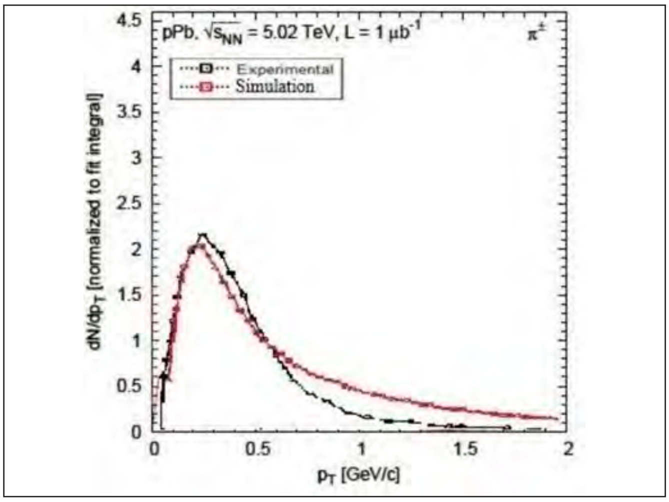

Figure 3. Transverse momentum distribution of opposite charged pions.

The K mesons, with a mass of approximately 500 MeV/c^2, are the lighter strange mesons, that can be produced in reactions of the type:

$$\pi^- + \pi \rightarrow \nu + K^+ + K- \quad (11)$$

The cross-section of these processes is of the range of millibarn, typical of processes that involve strong nuclear interaction, however, K mesons decay with a life time of 10^{-8}s, characteristic of the weak interaction. This is why different values from zero of strangeness are assigned to them. The invariant mass spectrum eliminating the peak of the π mesons was obtained in the simulation.

Two resonances were observed: 770 MeV/c^2 and 498 MeV/c^2, corresponding to the formation of ρ and K mesons, respectively, in agreement with experimental results.

C. Angular distribution and cross-section

In the incoherent processes, nucleus splitting can occur, with preferential emission of neutrons in the same direction of the incident photons. The figure shows the angular distribution of neutrons obtained in the simulation. It can be observed the expected maximum in the forward direction.

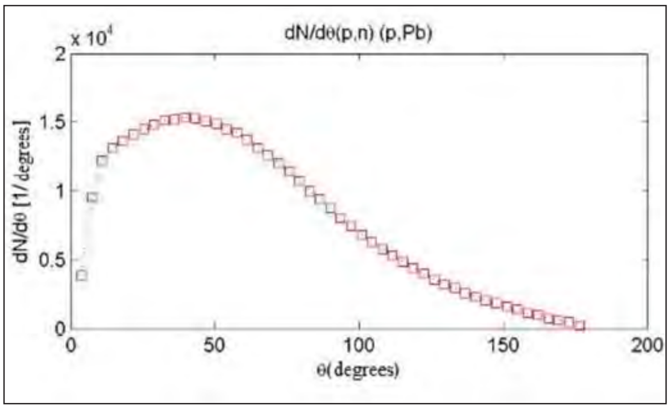

Figure 4. Angular distribution of neutrons in γ+Pb simulation at $\sqrt{s_{nn}} = 5{,}02$ TeV .

The neutron, proton and pion γ +^{197}Au photonuclear cross-sections were calculated. The cross-sections increase with the energy of the incident photon until a maximum value. From this point on, the cross-sections decrease as a result of the opening of other channels at higher energies.

The following figure shows the differential cross-sections, including the weigh-in of the spectrum for ^{197}Au. The inclusion of the weigh-in of the spectrum enables affirming that it has been passed from exploring the production of particles making photons collide with target nucleus, to the study of a process of ultra-peripheral nature, where the electromagnetic field of one of the nuclei has excited the other nucleus, causing emission of particles. When the weigh-in is included the higher energies are strongly suppressed, which indicates that the weigh-in of the spectrum is crucial if one wants to do comparisons between simulation and experiment in ultra-peripheral collisions.

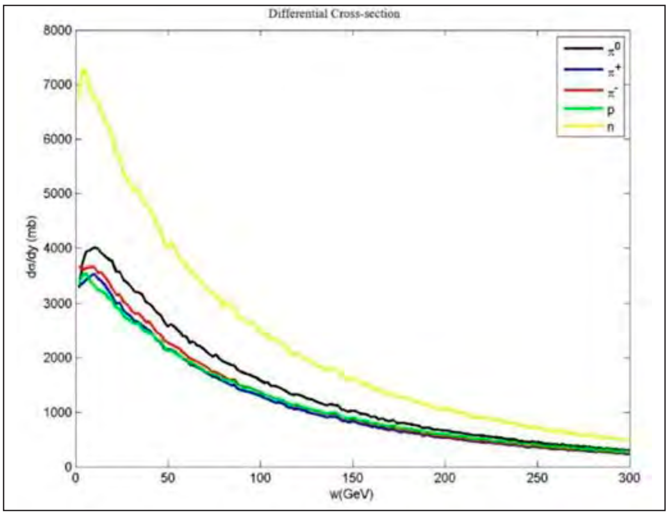

Figure 5. Neutron, proton and pion differential cross-section of ^{197}Au -^{197}Au at $\sqrt{s_{nn}} = 200$ GeV.

VI. Conclusions

In the present work the production of hadrons in photonuclear interactions γ-A of ultra-peripheral collisions is characterized. Firstly, the interaction of real photons with protons as target was simulated and the mesonic resonances for energies under 1 GeV were observed, obtaining in the simulation results in agreement with experimental data. Also a methodology for the study of ultra-peripheral collisions using the code CRISP is developed. The classical Weizsäcker-Williams method was implemented in MATLAB, for the symmetric case ^{197}Au-^{197}Au and asymmetric p-^{208}Pb, comparing it with more precise approximations reported in literature. It allowed validating the weigh-in performed in this contribution, and counting with the spectrums of the gold nucleus, the proton and the lead nucleus.

For the study of the ultra-peripheral asymmetric collision p-^{208}Pb at $\sqrt{s_{nn}} = 5{,}02$ TeV the hypothesis of the relative infrequency of the two photon events was followed. In both cases (^{197}Au-^{197}Au and p-^{208}Pb) magnitudes of interest were calculated: cross-section, differential cross-section, multiplicity, invariant mass spectrum, angular distribution and p_T distribution, obtaining good agreement with experimental results. Furthermore, in spite of collecting data of 10000 effective cascades in the code CRISP, a fairly poor statistic for the case of heavy mesons was obtained, which corroborates the experimental data obtained about their majority production in p-^{208}Pb in the γ-p processes [7].

The previously analysed results allow to confirm the efficiency of the Method of Virtual Photons to describe the production of hadrons due to the electromagnetic excitation of the nucleus, and the importance of the inclusion of the weigh-in of the spectrum. In the interest of completing the characterization of the ultra-peripheral asymmetric collision p-^{208}Pb, it is recommended to study the γ-p interactions, in all the energetic range of incidence of the incoming photons from the lead nucleus. It would allow extending this work including the production of heavy mesons because, as it was said previously, its majority rate of production in p-^{208}Pb is in the γ-p processes. For this, the research has to be done with a Monte Carlo simulator adequately describing binary interactions at higher energies. Furthermore, it could be extended taking into account the availability of experimental results, to other ultra-peripheral asymmetric collisions as d-Au, d-Pb, etc.

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