The Nuclear Matter Effects in π^0 Photoproduction at High Energies

T. E. Rodrigues[1], J. D. T. Arruda-Neto[1], J. Mesa[2], C. Garcia[1], K. Shtejer[1,3], D. Dale[4], and I. Nakagawa[5]
[1]*Physics Institute, University of São Paulo, P.O. Box 66318, CEP 05315-970, São Paulo, Brazil*
[2]*Department of Physics and Biophysics - UNESP, Botucatu, SP, Brazil*
[3]*Center of Applied Studies for Nuclear Developments (CEADEN), Havana, Cuba*
[4]*Department of Physics, Idaho State University, Pocatello ID, 83209, USA and*
[5]*RIKEN 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*

Received on 18 March, 2006

The in-medium influence on π^0 photoproduction from spin zero nuclei is carefully studied in the GeV range using a straightforward Monte Carlo analysis. The calculation takes into account the relativistic nuclear recoil for coherent mechanisms (electromagnetic and nuclear amplitudes) plus a time dependent multi-collisional intranuclear cascade approach (MCMC) to describe the transport properties of mesons produced in the surroundings of the nucleon. A detailed analysis of the meson energy spectra for the photoproduction on ^{12}C at 5.5 GeV indicates that both the Coulomb and nuclear coherent events are associated with a small energy transfer to the nucleus ($\lesssim$ 5 MeV), while the contribution of the nuclear incoherent mechanism is vanishing small within this kinematical range. The angular distributions are dominated by the Primakoff peak at extreme forward angles, with the nuclear incoherent process being the most important contribution above $\theta_{\pi^0} \gtrsim 2^0$. Such consistent Monte Carlo approach provides a suitable method to clean up nuclear backgrounds in some recent high precision experiments, such as the PrimEx experiment at the Jefferson Laboratory Facility.

Keywords: Meson photoproduction in-medium effects intranuclear cascade

I. INTRODUCTION

The total π^0 photoproduction cross section from complex nuclei can be evaluated as a sum of the electromagnetic part, known as the Primakoff effect[1], the nuclear coherent, the interference between the nuclear coherent and Primakoff amplitude and the nuclear incoherent contribution. The interference mechanism was neglected in this work since it consists of a genuine quantum process which is out of the context of the present semi-classical cascade calculation. While the electromagnetic part is almost non-sensitive to the Final State Interactions of the produced pions, the nuclear amplitudes are highly distorted by the medium and the complete nuclear ensemble should be taken into account in a realistic calculation.

In this paper we describe a sophisticated Monte Carlo method to address the dynamical evolution of an excited nuclear system. The calculation takes advantage of the Impulse Approximation (IA) to incorporate the interaction of the incoming photon with the nucleus in three different ways:

(1) a coherent electromagnetic interaction, where the pion is produced in the nuclear Coulomb field and, consequently, far away from the range of the nuclear potential which results in low Final State Interaction effects;

(2) a coherent nuclear production mechanism, where the pion is produced in the nuclear field and is susceptible to strong Final State Interactions, and;

(3) an incoherent photoproduction mechanism, where the pion is produced nearby a single nucleon, leaving the nucleus in an excited state and being also very sensitive to strong Final State Interactions.

These three scenarios apply, respectively, to the Primakoff, Nuclear Coherent and Nuclear Incoherent contributions for the total π^0 production cross section and are described in more detail below.

The main focus of this work consists in the determination of the nuclear background in high energy-forward angles π^0 photoproduction from spin zero nuclei, such as ^{12}C and ^{208}Pb. The calculation takes into account multiple scattering processes between the produced pions and the bound nucleons during the cascade stage. The Primakoff angular distribution is forward peaked because the Coulomb amplitude (γ^* exchange) goes as $1/t$, where t is the square of the four momentum transfer in the s channel (photoproduction channel) and also scales with the target charge and the square root of the $\pi^0 \to \gamma\gamma$ decay width. The measurement of this decay width, related to the $\gamma\gamma^*\pi^0$ coupling constant of the Quantum Chromodynamics (QCD) has been the subject of various experiments, like the one performed at Cornell[2], and is also a major issue in a recent experiment carried out at the Jefferson Laboratory Facility, the PrimEx Collaboration[3]. In this regard, the measurements of the π^0 angular distributions at forward angles, one of the PrimEx Collaboration's priorities, provide an indirect method to determine such an important and fundamental quantity.

II. THE INTRANUCLEAR CASCADE MONTE CARLO METHOD

The calculation outlined on this paper follows some previous work based on the Monte Carlo Multi-Collisional Intranuclear Cascade Model MCMC. Some improvements were incorporated to accommodate the Final State Interactions of the produced pions also for the nuclear coherent mechanisms, as well as the relativistic nuclear recoil for both the nuclear coherent and the electromagnetic (Primakoff) processes. The MCMC model was first developed to study high energy photonuclear reactions [4–7], being more recently successfully extended to intermediate energies[8, 9]. A special and very sophisticated version of the MCMC code were also proposed in a recent paper[10] in order to study the incoherent π^0 photoproduction both at the $\Delta(1232)$ resonance energy region, as well as in the $4.0-6.0$ GeV range and forward angles[10]. Such work showed the accuracy of the cascade model in predicting recent and intriguing results of the π^0 differential cross section for ^{12}C in the Delta region[11]. For details, see ref.[10] and references therein.

The MCMC model is essentially a typical transport calculation with some advantages related with the continuous time dependent structure available in the Monte Carlo analysis. Such an approach does not require a pre-determined time span between two successive collisions, like the well known BUU (Boltzmann-Uehling-Uhlenbeck) transport model [12, 13]. This special feature of the MCMC is related with the constant updating of the relativistic space-time, energy-momentum particle's four vectors along time.

III. THE π^0 PHOTOPRODUCTION MECHANISMS

A. The electromagnetic π^0 photoproduction mechanism

The differential cross section of the electromagnetic photoproduction of a pseudo-scalar meson P from a spin-zero nuclei may be written as[14]:

$$\frac{d\sigma_P}{d\Omega} = \Gamma_{P\to\gamma\gamma}\frac{8\pi\alpha Z^2}{m_P^3}\frac{\beta^3k^4}{Q^4}\left|F_{el}(Q)\right|^2\sin^2\theta_P, \qquad (1)$$

where $\Gamma_{P\to\gamma\gamma}, m_P, \beta$ and θ_P are, respectively, the radiative decay width, mass, velocity and polar angle of the pseudo-scalar meson P. Z is the charge of the nucleus, $F_{el}(Q)$ the nuclear electromagnetic form factor, k the incident photon energy and Q the four momentum transfer to the nucleus, with $\alpha = \frac{1}{137}$.

Eq.(1) indicates that the Coulomb production is forward peaked with its maximum at $\theta_{peak} \sim \frac{m_P^2}{2k^2}$. Such kinematical characteristic makes is possible to disentangle different production mechanisms in nuclei, shedding light to determine $\Gamma_{P\to\gamma\gamma}$ via angular distribution measurements.

Since the main subject on this paper is the nuclear contribution of the total π^0 photoproduction, we have neglected the FSI effects in the Coulomb contribution wherever it appears. The relativistic nuclear recoil was taken into account applying the relativistic energy and momentum conservation to the photon $-$ nucleus system, with the assumption that the whole nucleus has absorbed the momentum transfer Q, as it does in a coherent mechanism. With this approach, the complete kinematics of the interaction were determined by the meson polar angle, which was sampled in the Monte Carlo routine in accordance with eq.(1).

B. The nuclear coherent π^0 photoproduction mechanism

Following the steps elegantly delineated in ref.[14], we may write the nuclear coherent cross section as:

$$\frac{d\sigma_{NC}}{d\Omega} = L^2A^2\left|F_N(Q)\right|^2\sin^2\theta_P, \qquad (2)$$

where L is an angular-independent constant, A the nuclear mass and $F_N(Q)$ the strong nuclear form factor. The constant L can be interpreted as a free parameter and was taken as $L \approx 12.2k$ following the parameterization achieved for the Cornell data[2]. The nuclear coherent cross section peaks at approximately $\theta_{peak} \sim \frac{2}{kR}$, where R is the nuclear radius.

After being produced in the nuclear field, the pions are highly susceptible to FSI effects and may re-scatter in the nuclear matter, bringing the nucleus to an excited state. This process significantly changes the pion energies and angular distributions, attenuating eq.(2). Such a complex mechanism is out of the range of the conventional scattering theories, since various diagrams are relevant with the additional difficulty of dealing with many coupled channels. For this reason, the Monte Carlo method described here provides a powerful technique to address the correlation between coherent and incoherent processes via FSI.

The distortion effects on eq.(2) depend significantly on the nuclear volume and pion production energy. Besides it, nucleon-nucleon correlations due to the Pauli principle and the momentum distribution of the nucleons at the nuclear ground state play a key role for pion-nucleon scatterings at low polar angles (low momentum transfer).

C. The nuclear incoherent π^0 photoproduction mechanism

The total incoherent production amplitude is characterized by a sum of single nucleon amplitudes. The photon probes a high density nuclear environment and is supposed to interact with a single nucleon, bringing the nucleus to an excited state. The fundamental property of such mechanism is that no interference occurs between the accessible states and the nuclear cross section simply scales with the nuclear mass. So, the total incoherent cross section may be written as:

$$\frac{d\sigma_{NI}}{d\Omega} = A\xi(k,\theta)f(Q)\frac{d\sigma_N}{d\Omega}(k,\theta)\left[1+\lambda(k,\theta)\right], \qquad (3)$$

where ξ is the π^0 nuclear absorption, f is the Pauli-blocking suppression factor for small Q, $\frac{d\sigma_N}{d\Omega}$ is the photoproduction from the nucleon and λ is a factor accounting for the π^0 secondary production and re-scattering. The elementary photoproduction cross section $\frac{d\sigma_N}{d\Omega}$ can be written in terms of the helicity amplitudes, which are calculated in the context of the Regge theory under the assumption that the production process is largely dominated by vector meson (ρ and ω) exchange for low t. Such elementary operator was calculated in ref.[10], reproducing quite succesfully the proton data at few GeV[15, 16]. For details on the calculations of the helicity amplitudes see ref.[10] and references therein.

The nucleon-nucleon correlations and the momentum distribution of the ground state determine the Pauli-blocking factor f. Indeed, this suppression function significantly changes eq.(3) for low momentum transfer and is the crucial step in reproducing the structures on the π^0 differential cross section for ^{12}C near the Delta resonance[10, 11].

IV. THE TRANSPORT OF PIONS THROUGH THE NUCLEAR MATTER

To access the Final State Interactions between the produced pions on their way out of the nucleus it is important to take into account the most relevant scattering processes for a given πN channel. This analysis was already performed in a previous work[10], where we have included the following πN channels for $E_\pi \leq 6.0$ GeV: *i*) elastic scattering; *ii*) resonance production and decay; *iii*) charge exchange processes; *iv*) pion re-absorption by a nucleon pair, and *v*) multiple pion production processes (up to seven particles in the final state). Such multiple scattering scenario dictates how the initial π^0 flow is distributed among the available channels. In order to illustrate the rigorous Monte Carlo method to describe multiple pion-nucleon scatterings, we show in Fig. 1 the time derivative of the average number of pion-nucleon scatterings $\langle n_{\mathbf{int}} \rangle$ with and without the Pauli-blocking for a typical cascade at 6.0 GeV for ^{12}C and ^{208}Pb. The dependence of $\frac{d\langle n_{\mathbf{int}}\rangle}{dt}$ on the nuclear volume is evident, showing that secondary scatterings are not relevant in light nuclei. The result for ^{12}C exhibits a peak at the earliest cascade stages falling rapidly to zero around 5 fm/c. This gives a nice estimate ($\sim$ 5 fm) of the nuclear dimensions for a pion traveling at the speed of light. For the ^{208}Pb, however, we obtained a much broader distribution with a maximum shifted towards $\sim$ 5 fm/c, indicating that secondary scatterings with multiple pion productions are likely to occur for heavier systems.

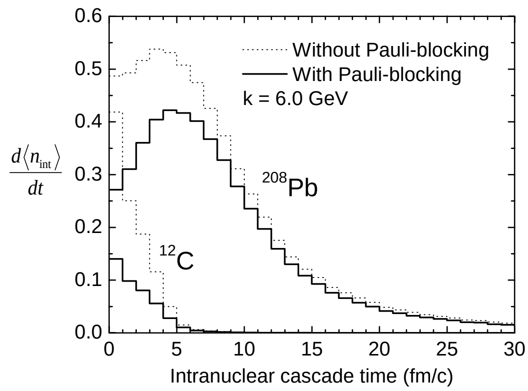

FIG. 1: Time derivative of the average number of pion-nucleon interactions during the cascade stage for ^{12}C and ^{208}Pb at 6 GeV. The dotted/solid histogram represents all the collisions without/with the Pauli exclusion principle.

V. RESULTS

A. π^0 angular distributions for ^{12}C at the GeV range and forward angles

With the prescriptions outlined above, we can calculate the angular distributions of neutral pions in the GeV range for the Primakoff, Nuclear Coherent and Nuclear Incoherent mechanisms. The results for ^{12}C at $k = 5.5$ GeV in the laboratory frame are shown in Figs. 2, 3 and 4. Kinematical cuts on the total π^0 energy were applied in order to estimate the nuclear background at different kinematical domains. The quantity ΔE represents the energy difference between the incoming photon and the outgoing pion: $\Delta E = k - E_{\pi^0}$. While for the coherent mechanisms (electromagnetic/nuclear) most of the pions have the total energy very close to the incident photon energy ($\Delta E \lesssim 3$ MeV), for the incoherent process (figure 4) there is a significant lowering on the pion energies caused by the requirement of a higher momentum transfer to excite the nucleus.

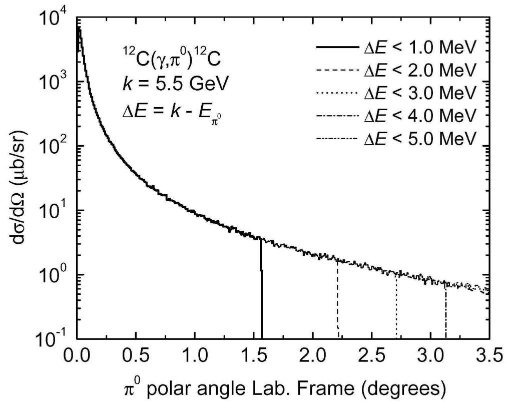

FIG. 2: Primakoff π^0 photoproduction cross section from ^{12}C at 5.5 GeV in the PWIA. The kinematical cuts are as follows: $\Delta E < 1$ MeV (solid), $\Delta E < 2$ MeV (dashed), $\Delta E < 3$ MeV (dotted), $\Delta E < 4$ MeV (dashed-dotted) and $\Delta E < 5$ MeV (dashed-dotted-dotted).

The Primakoff cross section (Fig. 2) exhibits a peak around $\frac{m_\pi^2}{2k^2} \sim 0.017$ degrees and falls rapidly to zero because of the $\frac{1}{Q^4}$ dependence. It is interesting to note that almost all the pions have total energy between k and $k - 1$ MeV. This result reflects the forward peak constraint imposed by eq.(1).

The nuclear coherent cross section (Fig. 3) peaks at approximately $\frac{2}{kR} \sim 1.49$ degrees, falling to zero for $\theta_{\pi^0} \gtrsim 3.5$ degrees. Most of the pions produced via the nuclear coherent mechanism have total energy between k and $k - 3$ MeV, in accordance with the kinematical characteristic inherent to eq.(2). The solid line of figure 3 represents the Plane Wave Impulse Approximation (PWIA), while the dashed line also includes the FSI effects of the produced pions.

The nuclear incoherent cross section is shown in Fig. 4.

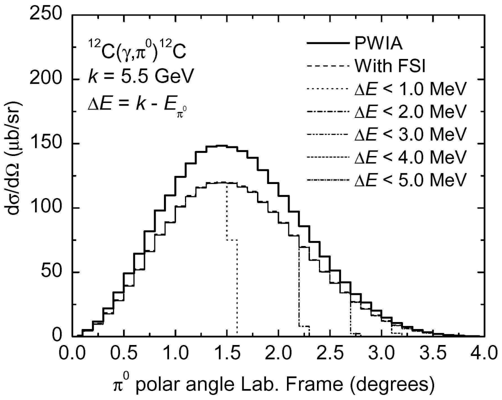

FIG. 3: Nuclear coherent π^0 photoproduction cross section from ^{12}C at 5.5 GeV. The solid histogram is the PWIA and the dashed histogram includes the FSI effects of the produced pions. The kinematical cuts are as follows: $\Delta E < 1$ MeV (dotted), $\Delta E < 2$ MeV (dashed-dotted), $\Delta E < 3$ MeV (dashed-dotted-dotted), $\Delta E < 4$ MeV (short-dashed) and $\Delta E < 5$ MeV (short-dashed-dotted).

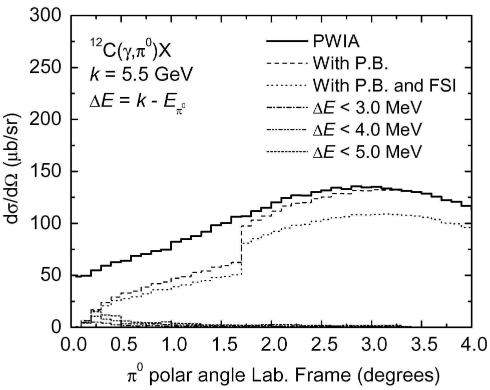

FIG. 4: Nuclear incoherent π^0 photoproduction cross section from ^{12}C at 5.5 GeV. The solid histogram is the PWIA, the dashed line takes into account the Pauli exclusion principle and the dotted line represents the full calculation with FSI. The kinematical cuts are as follows: $\Delta E < 3$ MeV (dashed-dotted), $\Delta E < 4$ MeV (dashed-dotted-dotted) and $\Delta E < 5$ MeV (short-dashed).

The PWIA is the solid line and the dashed line represents the calculations including the Pauli exclusion principle. The full calculation is the dotted line and takes into account the FSI effects. The structures of the cross section for low polar angles are attributed to the kinematics of the photoproduction channel, which takes into account the Pauli principle and a realistic momentum distribution of the nucleons at the ground state based on the shell model. For details on the momentum distributions see ref.[10]. The kinematical cuts on the incoherent cross section are very effective, showing that only few

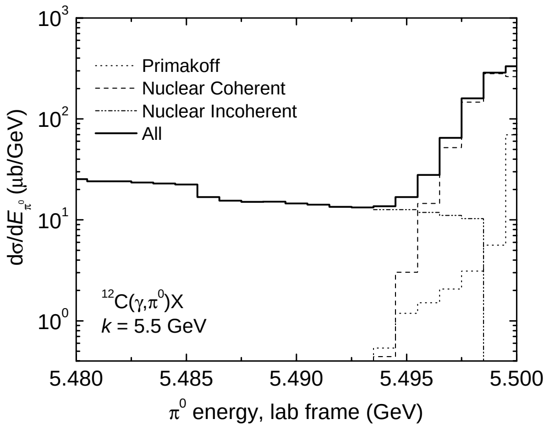

FIG. 5: π^0 energy spectra for ^{12}C at 5.5 GeV and its Primakoff (dotted), nuclear coherent (dashed) and nuclear incoherent (dashed-dotted-dotted) contributions.

events can survive after a typical cut $\Delta E < 5$ MeV.

B. π^0 energy spectra for ^{12}C at the GeV range and forward angles

The neutral pion energy spectra can be combined with the angular distributions to disentangle the different production processes in nuclei. The structure of the MCMC model permits a continuous evaluation of particle's energies along time, propitiating an accurate method to access information of an excited nuclear system.

Figure 5 shows the normalized π^0 energy spectra for ^{12}C at $k = 5.5$ GeV for the three different production channels. The Primakoff contribution (dotted line) exhibits a remarkable peak at $\Delta E < 1$ MeV, as suggested by the angular distribution results. The nuclear coherent processes (dashed line) is also concentrated at the higher energy region, typically $\Delta E < 5$ MeV, and dominates the photoproduction mechanism due to the small fraction of Primakoff events on the total (integrated) cross section. Both of the coherent processes are not relevant above $\Delta E \sim 6$ MeV, since the respective form factors vanish at this kinematical domain ("high" momentum transfer region). The nuclear incoherent π^0 energy spectrum (dashed-dotted-dotted line) is spread almost uniformly for lower pion energies. This contribution vanishes below the Primakoff peak as it demands a much higher momentum transfer in order to excite the nucleus. It is worth noting, however, that both the angular distributions and the pion spectra do not uniquely determine the type of photoproduction mechanism as different processes can take place at the same angular/energy interval. In fact, the nuclear incoherent contribution for high energy pions ($\Delta E \lesssim 5$ MeV) is substantially attenuated (figure 4) and the investigation of the pion spectra at these energies may serve as an additional constraint to clean up the incoherent contribution.

VI. CONCLUSIONS

A Monte Carlo method has been applied to study both coherent (Primakoff/nuclear) and incoherent π^0 photoproduction mechanisms at the GeV range and forward angles from spin zero nuclei. The Coulomb process was analyzed taking into account the exact relativistic recoil of the nucleus and neglecting FSI effects of the produced pions (PWIA). The other processes, namely, the nuclear coherent and incoherent contributions were analyzed in the context of the MCMC intranuclear cascade model including full FSI effects.

The differential cross sections for ^{12}C at 5.5 GeV are largely dominated by the Primakoff peak up to $\theta_{\pi^0} \lesssim 0.5^0$, with the nuclear coherent mechanism being the most relevant contribution in the range $0.5^0 \lesssim \theta_{\pi^0} \lesssim 2.0^0$. The nuclear incoherent part is Pauli-suppressed at lower angles and becomes the largest contribution for higher angles $\theta_{\pi^0} \gtrsim 2.0^0$. The energy spectra of the pions indicate that both the Coulomb and nuclear coherent processes are concentrated within a narrow energy range ($\Delta E \lesssim 5$ MeV) in contrast to the nuclear incoherent part, which is greatly inhibited in this energy gap due to a much larger momentum transfer to the nucleus.

In conclusion, a careful kinematical analysis using the MCMC model was performed to establish an efficient method of background subtraction for future reference in high energy π^0 photoproduction experiments, such as the PrimEx Collaboration at the Jefferson Laboratory.

The authors thank the Brazilian agencies FAPESP and CNPq, and the Latin-American Physics Center (CLAF) for partial support to this work.

---

[1] H. Primakoff, Phys. Rev. **81**, 899 (1951).
[2] A. Browman, J. De Wire, B. Gittelman, K. M. Hanson, D. Larson, E. Loh, and R. Lewis, Phys. Rev. Lett. **33**, 1400 (1974).
[3] http://www.jlab.org/primex/primex_notes/PR99-014.ps (PrimEx Proposal, accessed in Aug-2006)
[4] M. G. Gonçalves, S. de Pina, D. A. Lima, W. Milomen, E. L. Medeiros, and S. B. Duarte, Phys. Lett. B **406**, 1 (1997).
[5] M. G. Gonçalves, E. L. Medeiros, and S. B. Duarte, Phys. Rev. C **55**, 2625 (1997).
[6] S. de Pina, E. C. Oliveira, E. L. Medeiros, S. B. Duarte, and M. Gonçalves, Phys. Lett. B **434**, 1 (1998).
[7] S. B. Duarte (private communication).
[8] T. E. Rodrigues, J. D. T. Arruda-Neto, A. Deppman, V. P. Likhachev, J. Mesa, C. Garcia, K. Shtejer, G. Silva, S. B. Duarte, and O. A. P. Tavares, Phys. Rev. C **69**, 064611 (2004).
[9] T. E. Rodrigues, PhD thesis, University of São Paulo (2005).
[10] T. E. Rodrigues, J. D. T. Arruda-Neto, J. Mesa, C. Garcia, K. Shtejer, D. Dale, and I. Nakagawa, Phys. Rev C **71**, 051603(R) (2005).
[11] B. Krusche et al., Eur. Phys. J. A **22**, 277 (2004).
[12] M. Effenberger, E. L. Bratkovskaya, and U. Mosel, Phys. Rev. C **60**, 044614 (1999).
[13] J. Lehr, M. Effenberger, and U. Mosel, Nucl. Phys. A **671**, 503 (2000).
[14] C. A. Engelbrecht, Phys. Rev. **133**, B988 (1964).
[15] M. Braunschweig, W. Braunschweig, D. Husmann, K. Lübelsmeyer, and D. Schmitz, Nucl. Phys. B **20**, 191 (1970).
[16] R. L. Anderson, D. B. Gustavson, J. R. Johnson, I. D. Overman, D. M. Ritson, B. H. Wiik, and D. Worcester, Phys. Rev. D **4**, 1937 (1971).