CONTRIBUTION OF THE $\Delta(1232)$ RESONANCE IN THE PION PHOTOPRODUCTION ON CARBON-12

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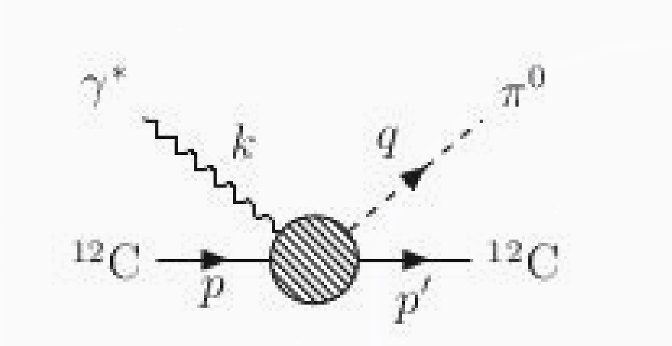
Introduction

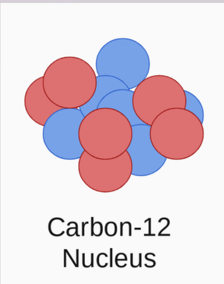
Since the elementary process $(\gamma + N \rightarrow \pi^0 + N)$ is highly dominated by the resonant $\Delta(1232)$, the photoproduction of neutral pions on complex nuclei is one of the most important tools to study production, decay and propagation of the $\Delta(1232)$ resonance in nuclear medium.



Generally the meson production near threshold provide a clean study approach to investigate in-medium production and propagation of the $\Delta(1232)$ resonance. Moreover π^0 production on ^{12}C is one of the most simplest systems among the vast complexity of nuclei.

Impulse Approximation

The model cross section is based on the impulse approximation where **free-nucleon** amplitudes describe photoproduction from each bound nucleon.



6 neutrons + 6 protons = ^{12}C

Elementary reactions with nucleons contributing within the $\gamma + {}^{12}\text{C} \rightarrow \pi^0 + {}^{12}\text{C}$ reaction.

$$\begin{aligned} \gamma + p &\rightarrow \pi^0 + p \\ \gamma + p &\rightarrow \pi^0 + n \end{aligned} \tag{1}$$

In the Plane-Wave-Impulse-Approximation (PWIA) the differential cross section in the π^{12}C frame is given by

$$\frac{k}{q}\frac{d\sigma_{\text{PWIA}}}{d\Omega_\pi} = \frac{1}{2J_i+1}\sum_{\lambda M_i M_f}\left|\left\langle i\left|\sum_i M_{\gamma\pi}(i)\right|f\right\rangle\right|^2 \tag{2}$$

The elementary nucleon photoproduction operator $M_{\gamma\pi}(i)$ is given by

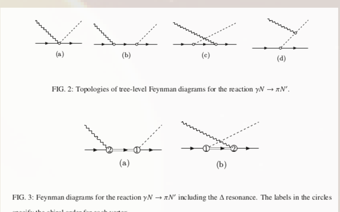
$$M_{\gamma\pi}(i) = [i\vec{\sigma}\cdot\vec{K} + L]_i e^{i\vec{Q}\cdot\vec{r}_i}, \qquad L = \hat{q}\times\hat{k}\cdot\hat{\epsilon}_\lambda P_3 \tag{3}$$

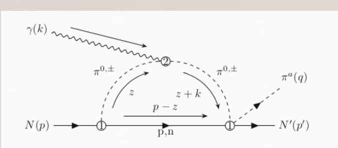
where $\vec{Q} = \vec{k} - \vec{q}$ is the nuclear momentum transfer and P_3 is the corresponding spin σ independent P-wave amplitude.

Elementary amplitudes in χPT

Chiral Perturbation Theory (χPT) is a succesful EFT of QCD that works at low energies, where QCD is non-perturbative. The relevant degrees of freedom are in consequence the confined states, i.e. the hadrons and their interactions are organized in expansions of small momenta and pion masses. The strong interactions among pions, nucleons and their resonances $\Delta(1232)$ are described within the chiral invariant Lagrangian [1]

$$\mathcal{L}_{\chi PT} = \mathcal{L}_{\pi\pi} + \mathcal{L}_{N\pi} + \mathcal{L}_{\Delta\pi} + \cdots \tag{4}$$





The low-energy hadron interactions are parametrized by low-energy-constants (LECs) that has been determined by experimental data, for example the $\pi^{0,+}$ photo- and electroproduction on nucleons Refs. [2] [3] and the $\Delta(1232)$ decay rates. Here, very few of them were used to make predictions at the nucleus level. The P-wave function P_3 Eq. (3) for the elementary $\gamma + N \rightarrow \pi^0 + N$ is extracted from the χPT amplitudes $\mathcal{F}_j^{(N)}$

$$P_3^{(N)} = \int_{-1}^{1}\frac{dx}{2}[\mathcal{P}_0(x) - \mathcal{P}_2(x)]\mathcal{F}_2^{(N)} \qquad x = \cos\theta_\pi \tag{5}$$

Coherent π^0 photoproduction on ^{12}C

For the particular case where the initial and final nucleus states are the same and the total spin is zero, the PWIA cross section Eq. (2) reduces to the elastic case

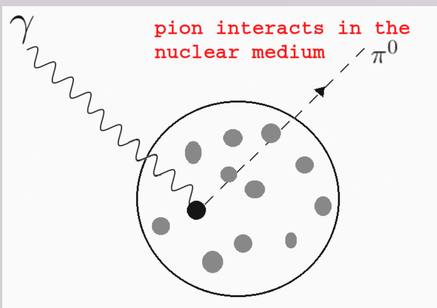
$$\frac{d\sigma_{0+}}{d\Omega_\pi} = \frac{A^2}{2}\frac{q}{k}\underbrace{\left[p_3^{(+)}kq\right]^2}_{\pi N\ \text{frame}} F^2(Q)\sin^2\theta_\pi \tag{6}$$

$$\text{with } p_3^{(+)} = \frac{1}{2}\left(p_3^{(p)} + p_3^{(n)}\right) \tag{7}$$

$A = 12$ and $F^2(Q)$ is nuclear form factor. At low energy the P-wave behaviour is reduced to $P_3^{(+)} = p_3^{(+)}kq$ which is a frame invariant [4] and derives directly from the free-nucleon reduced amplitudes.

Distorted-Wave Impulse-Approximation

At difference with the PWIA, where one has considered that the pion field is propagated in a plane wave, as well as the photon, in the DWIA we consider that the outcoming pion interacts in the nuclear medium, producing a complete set of pion-nucleus final states. This distorted-pion final state is taken into account by an standard procedure by considering an optical potential which acts as perturbation with the interaction term for the pion photoproduction process.



In the near threshold energy R is approximately constant:

$$d\sigma_{\text{DWIA}} = R\,d\sigma_{\text{PWIA}}; \implies R = \frac{\sigma_{\text{DWIA}}}{\sigma_{\text{PWIA}}} \approx 1.3 \tag{8}$$

Incoherent photoproduction

The incoherent (inelastic) nuclei reactions of the type

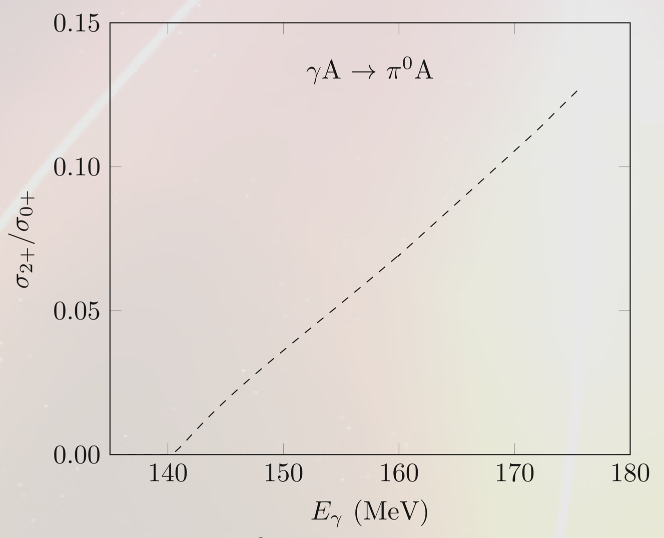
$$\gamma + {}^{12}\text{C} \longrightarrow \pi^0 + X. \tag{9}$$

can be considered for any distinct final nucleus X, for instance the contribution of the $J^P = 2^+$ produced near 4.4 MeV above threshold.

As in ref. [5], the cross section data is properly described far from threshold by taking into account the inelastic transition through the final nucleus ^{12}C state, $J^P = 2^+$(4.43 MeV). The corresponding PWIA expression for the angular cross section is

$$\frac{d\sigma_{2+}}{d\Omega_\pi} = \eta\frac{A^2}{2}\left(\frac{q}{k}\right)\left[p_3^{(+)}\right]^2 F_{2+}^2(Q)\sin^2\theta_\pi \tag{10}$$

the normalization η limits on the contribution of the 2^+ state to the C(γ,π^0) data, necessary since this state is unresolved. η is fixed to $\sigma_{2+}/\sigma_{0+} \sim 0.6 - 0.1$ as observed by experimental data [6]. Then $\eta \approx 1.5 - 2$ as suggested in [4].



Relative contribution of the inelastic cross section with respect to the elastic one as a function of energy.

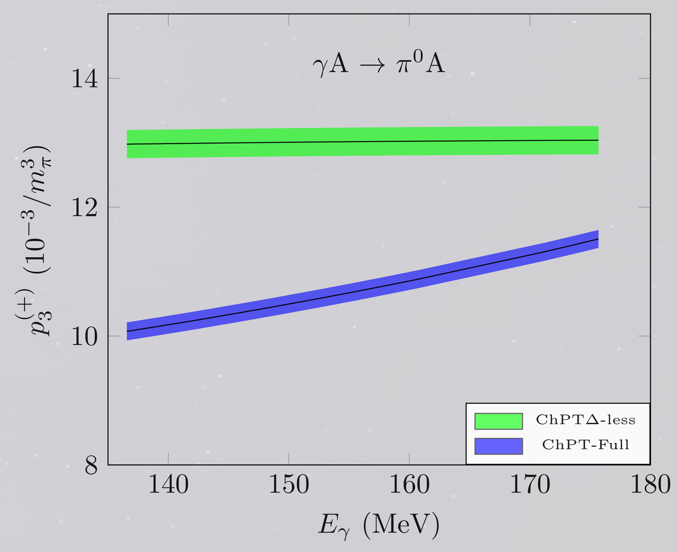
Considering the DWIA and the first two elastic and inelastic reactions, the total semi-inclusive cross section is then

$$\sigma_{\text{DWIA}} = R(\sigma_{0+} + \sigma_{2+}) \tag{11}$$

where the pion is equally distorted by both states

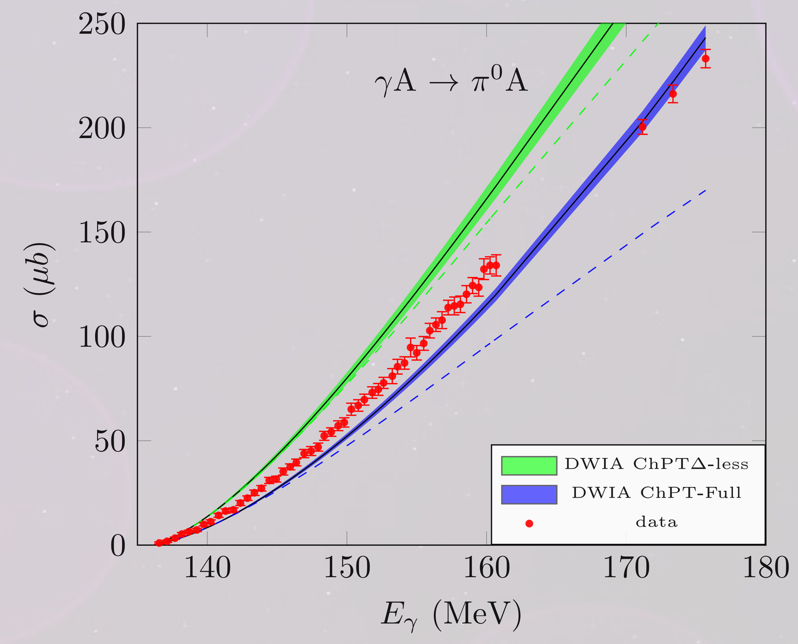
Predictions from χPT parameters

Results for the reduced amplitude $p_3^{(+)}$: obtained from LECs fitted to other experiments (π^+-electroproduction on nucleons, Δ strong and EM decay, p and n magnetic moments, πN scattering,...)



Energy dependence for the elementary function $p_3^{(+)}$ in the πN frame, comparing the full-model (blue) and the Δ-less model (green). The Δ field induces a stronger energy dependence at low energies.

Contributions of the $\Delta(1232)$ resonance



Results of the ^{12}C(γ,π^0) reaction from the χPT elementary amplitudes. Solid bands show the total DWIA cross sections as evaluated in Eq. (11). Dashed curves shows the effect of removing the incoherent (4.43 MeV) contribution. Data below 161 MeV are from [5] while the three points at higher energy are from [7]

Conclusions

- The increase of cross section is stronger when including incoherent production which reflects the increasing number of possible final states.
- The calculation neglecting the final state interactions (PWIA) fails to reproduce the measured cross sections. DWIA is known to be a good assumption.
- The $\Delta(1232)$ field induces a stronger energy dependence at low energies than other FSI or inelastic effects.
- $\Delta(1232)$ seems to be necessary to reproduce well the ^{12}C(γ,π^0), as well as in the elementary π^0 production on nucleons
- χPT is successful making predictions through the hadron degrees of freedom.

References

References

[1] G. H. Guerrero Navarro, M. Vicente Vacas, A. N. H. Blin and D.-L. Yao, *Pion photoproduction off nucleons in covariant chiral perturbation theory*, *Phys. Rev. D* **100** (2019) 094021, [1908.00890].

[2] G. H. Guerrero Navarro and M. J. Vicente Vacas, *Threshold pion electro- and photoproduction off nucleons in covariant chiral perturbation theory*, *Phys. Rev. D* **102** (2020) 113016, [2008.04244].

[3] A. N. Hiller Blin, T. Ledwig and M. J. Vicente Vacas, *$\Delta(1232)$ resonance in the $\vec{\gamma}p \rightarrow p\pi^0$ reaction at threshold*, *Phys. Rev.* **D93** (2016) 094018, [1602.08967].

[4] J. Bergstrom, *Photopion P wave multipoles near threshold from C-12 (gamma, pi0) and H-1 (gamma, pi0)*, *Phys. Rev. C* **50** (1994) 2979–2994.

[5] J. Bergstrom, R. Igarashi and J. Vogt, *Measurement of the ^{12}C(γ,π^0) reaction near threshold*, *Phys. Rev. C* **55** (1997) 2923–2930.

[6] G. Koch et al., *Cross-sections and Angular Distributions for ^{12}C (γ,π^0)*, *Phys. Lett. B* **218** (1989) 143–147.

[7] R. W. Gothe, Ph.D. thesis, Mainz University, 1990.

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