Coherent Photoproduction of Pseudoscalar Mesons in a Relativistic Framework

J. Piekarewicz[1], L. J. Abu-Raddad[1], M. Benmerrouche[2], and A. J. Sarty[1]
[1]*Florida State University, Tallahassee, FL 32306, USA*
[2]*University of Saskatchewan, Saskatoon, SK S7N 5C6, Canada*

Abstract

The coherent photoproduction of pseudoscalar mesons is studied in a relativistic impulse approximation approach. We show—on the basis of very general arguments—that the coherent reaction from $J^{\pi}=0^{+}$ nuclei is characterized by a single Lorentz invariant form factor. We evaluate this nuclear form factor without recourse to a nonrelativistic reduction. We show that the nuclear structure information is fully contained in the ground-state tensor density. The tensor density—which is essentially unconstrained by experiment—is evaluated in a mean-field approximation to the Walecka model.

The coherent photoproduction of pseudoscalar mesons (such as π^0, η, and η') offers a unique opportunity for the investigation of nucleon-resonance formation and propagation through the nuclear medium. The advent of more powerful and sophisticated machines—such as TJNAF and MAMI—will challenge, now more than ever, our theoretical understanding of this fundamental process. The coherent reaction offers numerous advantages. Because the nucleus remains in its ground state, all nucleons participate coherently in the reaction. Theoretically, the coherent process acts as a spin-isospin filter by selecting a particular (scalar-isoscalar) component of the elementary photoproduction amplitude. In this way the reaction can be used to discriminate between various theoretical models that provide an equally good description of the elementary process. Moreover, all nuclear structure information is contained in, at most, a few ground-state densities. Indeed, nonrelativistic plane-wave-impulse-approximation analyses suggest that the photonuclear amplitude is directly proportional to the isoscalar (or matter) density [1, 2, 3, 4, 5]. Finally, because the coherent process is sensitive to the whole nuclear volume, one can place stringent limits on the form of the meson-nucleus optical potential.

Most theoretical analyses of the elementary process start with a model-independent parameterization of the photoproduction amplitude in terms of four Lorentz- and gauge-invariant amplitudes [6]. It is then customary to evaluate this amplitude between on-shell nucleon spinors, thereby leading to the well known CGLN form for the photoproduction operator in terms of Pauli—rather than Dirac—spinors [6]. For the calculation of the photonuclear reaction one usually adopts the impulse approximation [1, 2, 3, 4, 5]; one assumes that the elementary (on-shell) amplitude is not modified in the many-body environment. For closed-shell (spin-saturated) nuclei the photonuclear process then becomes, in the plane-wave limit, a simple product of the elementary scalar-isoscalar amplitude times the Fourier transform of the ground-state matter density. One then improves on the plane-wave description by incorporating distortions into the propagation of the outgoing meson. In this contribution we report on a similar theoretical program—without recourse to a nonrelativistic reduction of the elementary amplitude. The main difference relative to the standard nonrelativistic approach stems from the fact that in the present framework the lower components of the nucleon spinors will be determined dynamically, rather than from the free-space relation. The nuclear structure information will be contained in a few ground-state densities that will be computed using a mean-field approximation to the Walecka model [7].

The most general form for the amplitude for the coherent photoproduction reaction from $(J^\pi = 0^+; T = 0)$ nuclei can be written in the following way:

$$\langle A(p'); \mathrm{meson}(q)|T_\lambda|A(p); \gamma(k)\rangle \equiv \varepsilon^{\mu\nu\alpha\beta}\epsilon_\mu k_\nu q_\alpha p_\beta \frac{1}{W} F_0(s,t) \; . \tag{1}$$

Here ϵ_μ is the polarization vector of the photon, $p(p' = p + k - q)$ is the four momentum of the initial(final) nucleus and $\varepsilon^{\mu\nu\alpha\beta}$ is the relativistic Levi-Civita symbol. Note that all the dynamical information about the coherent process is contained in a single Lorentz-invariant form factor $F_0(s,t)$, which depends on the Mandelstam variables $s = (k+p)^2$ and $t = (k-q)^2$. One can now carry out the appropriate algebraic manipulations to obtain the following—model-independent—form for the coherent photoproduction cross section in the center-of-momentum (c.m.) frame:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{c.m.}} = \left(\frac{M_T}{4\pi W}\right)^2 \left(\frac{q_{\mathrm{c.m.}}}{k_{\mathrm{c.m.}}}\right) \left(\frac{1}{2} k_{\mathrm{c.m.}}^2 q_{\mathrm{c.m.}}^2 \sin^2\theta_{\mathrm{c.m.}}\right) |F_0(s,t)|^2 \; . \tag{2}$$

Here M_T is the mass of the target nucleus, $\theta_{\mathrm{c.m.}}$ is the scattering angle and W is the total energy in the c.m.-frame, while $k_{\mathrm{c.m.}}$ and $q_{\mathrm{c.m.}}$ are the three-momentum of the photon and meson, respectively.

We now proceed to compute the Lorentz invariant form factor in a relativistic impulse approximation. For the elementary $\gamma N \to \eta N$ amplitude we use a model-independent parameterization given in terms of four Lorentz- and gauge-invariant amplitudes [6]. Here, we cast the elementary amplitude so that the parity and Lorentz transformation properties of the various bilinear covariants become manifest:

$$T(\gamma N \to \eta N) = \left(F_T^{\alpha\beta}\sigma_{\alpha\beta} + F_P\gamma_5 + F_A^\alpha\gamma_\alpha\gamma_5\right) \; . \tag{3}$$

Note that tensor, pseudoscalar, and axial-vector amplitudes have been introduced; these are written in terms of the four elementary amplitudes for the photoproduction process [8]. Moreover, for this particular form of the elementary amplitude no scalar nor vector invariants appear. For closed-shell nuclei an enormous simplification ensues, as a result of the pseudoscalar and axial-vector ground-state densities being identically zero. This implies that the coherent reaction is sensitive to only one component (the so-called A_1 amplitude) of the elementary amplitude. Further, all the nuclear-structure information is contained in the ground-state tensor density [7]. This is in contrast to nonrelativistic approaches in which the coherent amplitude is proportional to the conserved vector density [1, 2, 3, 4, 5]. Thus, in a relativistic plane-wave impulse approximation, the Lorentz-invariant form factor acquires a remarkable simple form:

$$F_0^{PW}(s,t) = iA_1(\tilde{s},t)\rho_{{}_T}(Q)/Q \; . \tag{4}$$

Note that $\tilde{s}$ represents the effective (or optimal) value of the Mandelstam variable s at which the elementary amplitude should be evaluated [2] and $Q \equiv |\mathbf{k}_{\mathrm{c.m.}} - \mathbf{q}_{\mathrm{c.m.}}| \simeq \sqrt{-t}$.

The ground-state tensor density is evaluated in a mean-field approximation to the Walecka model. For spin-saturated nuclei only three ground-state densities do not vanish [7]; these are the scalar and timelike-vector densities—used to compute the mean-field ground state—and the tensor density. For the coherent reaction it is only the Fourier transform of the latter that is needed. The tensor density is linear in the lower (or small) component of the single-particle wave function. Thus, the tensor density is interesting because it is sensitive to the relativistic components of the wave function. Indeed, the mean-field approximation to the Walecka model is characterized by the existence of large Lorentz scalar and vector potentials that are responsible for a substantial enhancement of the lower components of the single-particle wave functions.

We illustrate our formalism by calculating the coherent photoproduction of η mesons from ^{40}Ca. The elementary η-production amplitude used here is constructed in an effective Lagrangian approach as detailed in references [9, 10]. As is well known, the $S_{11}(1535)$ resonance clearly dominates the elementary reaction. However, when embedded into the coherent reaction from closed-shell nuclei, intermediate $S_{11}(1535)$ excitation is suppressed due to spin-isospin considerations. Indeed, it is just this suppression of the dominant s-wave term—allowing enhancement of the non-dominant contributions—which initially provoked interest in this coherent reaction [3]. Finally, distortion effects are incorporated through an η-nucleus optical potential that is computed in a simple "$t\rho$" approximation [3]. In Fig. 1

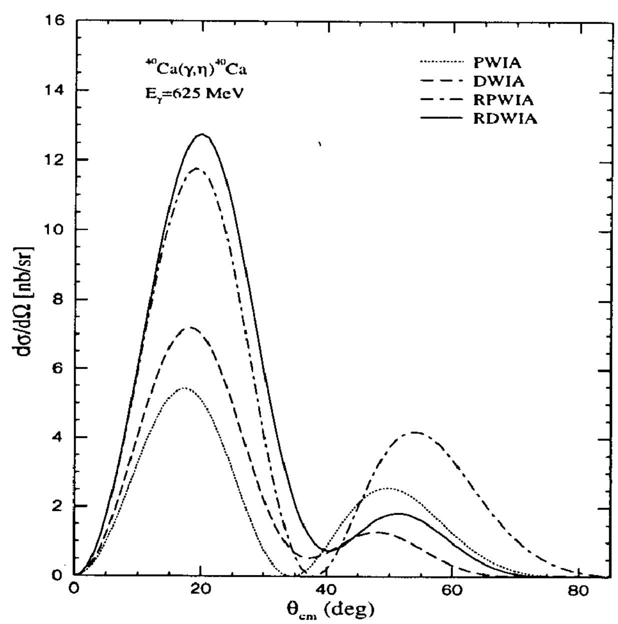

Figure 1: The coherent η-photoproduction cross section from ^{40}Ca at $E_\gamma = 625$ MeV.

we display the coherent η-photoproduction cross section from ^{40}Ca at a photon laboratory energy of $E_\gamma = 625$ MeV. The dotted line represents a plane-wave calculation in which the lower components of the single-particle wave functions were determined from the free-space relation; this represents our best attempt at reproducing standard nonrelativistic calculations. Indeed, in this "nonrelativistic" limit there is a simple relation between the tensor and vector densities of closed-shell nuclei:

$$\rho_T(Q) \approx -\frac{Q}{2M_N}\rho_V(Q) \,, \tag{5}$$

where M_N is the free nucleon mass and $\rho_V(Q)$ is the Fourier transform of the ground-state vector density. This picture, however, changes dramatically once the lower components of the wave functions are determined dynamically, rather than from the free-space relation. In the particular case of the Walecka model the lower components are enhanced substantially in the medium as a consequence of the large scalar and vector mean-field potentials. Since the coherent cross section becomes dominated by the tensor density, we obtain a relativistic plane-wave cross section (dot-dashed line) that is, at least, twice as large as its nonrelativistic counterpart. Note that the distortions effects are relatively small at this low energy for both calculations.

To conclude, we address several possible complications to the simple picture presented here. First, in the impulse approximation one assumes that the elementary amplitude—which only contains on-shell information—can be used without modification in the nuclear medium. However, the formation, propagation, and decay of intermediate resonances—an important component of all microscopic models—are likely to be modified in the many-body environment. Thus, it is important to have a reliable microscopic model in which to test the validity of the impulse approximation. A microscopic model can also provide guidance on how to take the elementary amplitude off-shell. The form of the elementary amplitude used here, although standard, is not unique. Many other choices—all of them equivalent on shell—are possible. While all these choices are guaranteed to give identical results for on-shell observables, they can yield vastly different predictions off-shell. Without theoretical guidance, there is no hope of resolving the off-shell ambiguity. Indeed, much work remains to be done—on both theoretical and experimental fronts—before a clear picture of the coherent process can emerge.

References

1. S. Boffi and R. Mirando, Nucl. Phys. **A448**, 637 (1986).
2. A.A. Chumbalov, R.A. Eramzhyan, and S.S. Kamalov, Z. Phys. **A328**, 195 (1987).
3. C. Bennhold and H. Tanabe, Phys. Lett. B **243**, 13 (1990); Nucl. Phys. **A530**, 625 (1991).
4. A. Nagl, V. Devanathan, and H. Überall, *Nuclear Pion Photoproduction,* (Springer-Verlag, Berlin Heidelberg, 1991)
5. V.A. Tryasuchev and A.I. Fiks, Phys. Atom. Nucl. **58**, 1168 (1995).
6. G.F. Chew, M.L. Goldberger, F.E. Low, and Y. Nambu, Phys. Rev. **106**, 1345 (1957).
7. J.D. Walecka, Ann. of Phys. **83**, 491 (1974); B.D. Serot and J.D. Walecka, Adv. in Nucl. Phys. **16**, J.W. Negele and E. Vogt, eds. (Plenum, N.Y. 1986).
8. J. Piekarewicz, A. J. Sarty, and M. Benmerrouche Phys. Rev. C **55**, 2571 (1997); L.J. Abu-Raddad, J. Piekarewicz, A.J. Sarty, and M. Benmerrouche, Phys. Rev. C **57**, 2053 (1998).
9. M. Benmerrouche, Ph.D. thesis, Rensselaer Polytechnic Institute, 1992.
10. M. Benmerrouche, J.-F. Zhang and N.C.Mukhopadhyay, Phys. Rev. D **51**, 3237 (1995); N.C. Mukhopadhyay, J.-F. Zhang and M. Benmerrouche, Phys. Lett. B **364**, 1 (1995).